The Sounds of Spacetime

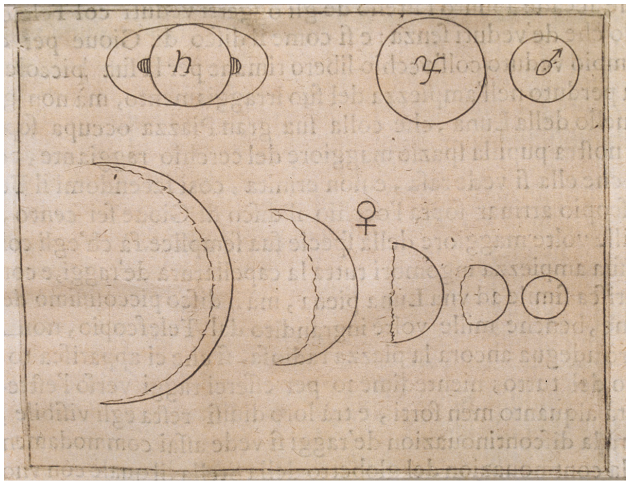
Black Holes, Early Universe, Cosmic Strings, and Holographic Noise

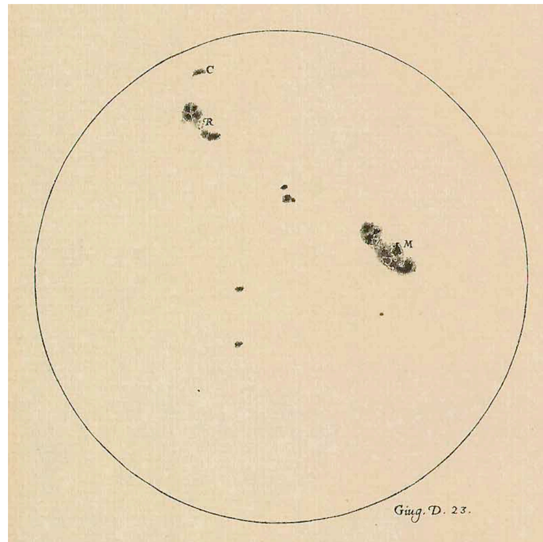
C. Hogan

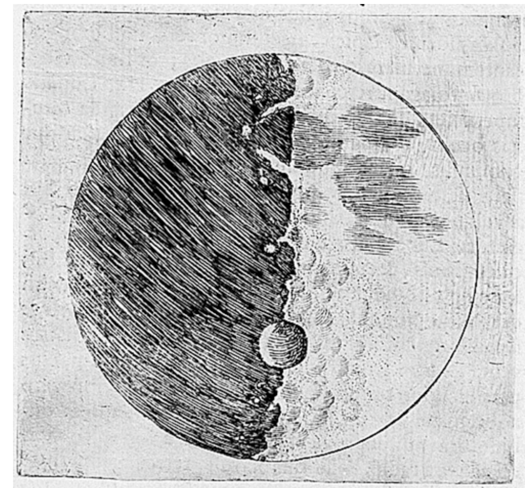
Fermilab and the University of Chicago

How often does science explore something really new?

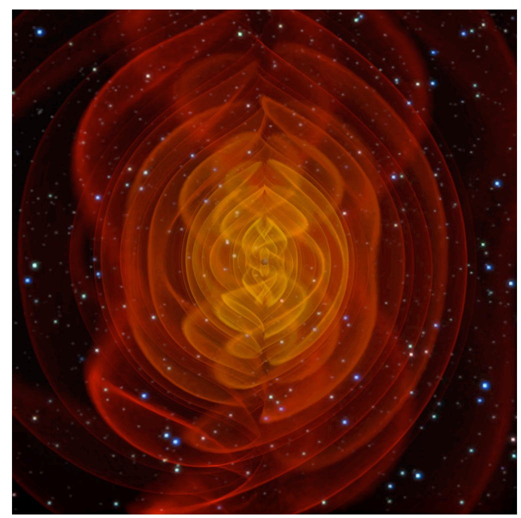
- 400 years ago: Galileo’s telescope







- Today (soon!): gravitational waves



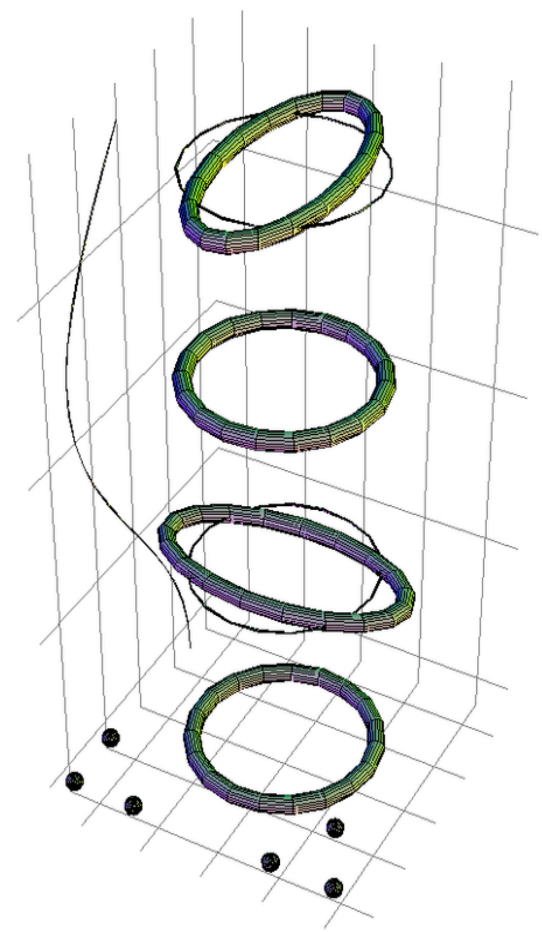
Gravitational Waves: a New Science

- Telescopes extend the human sense of sight
- Gravitational wave detectors extend hearing
- Light: electromagnetic radiation from accelerating particles
- Gravitational radiation: from accelerating mass-energy
- can deeply and precisely probe new phenomena not observable with light and never observed before
- 95% of the mass-energy of the universe does not interact with light!

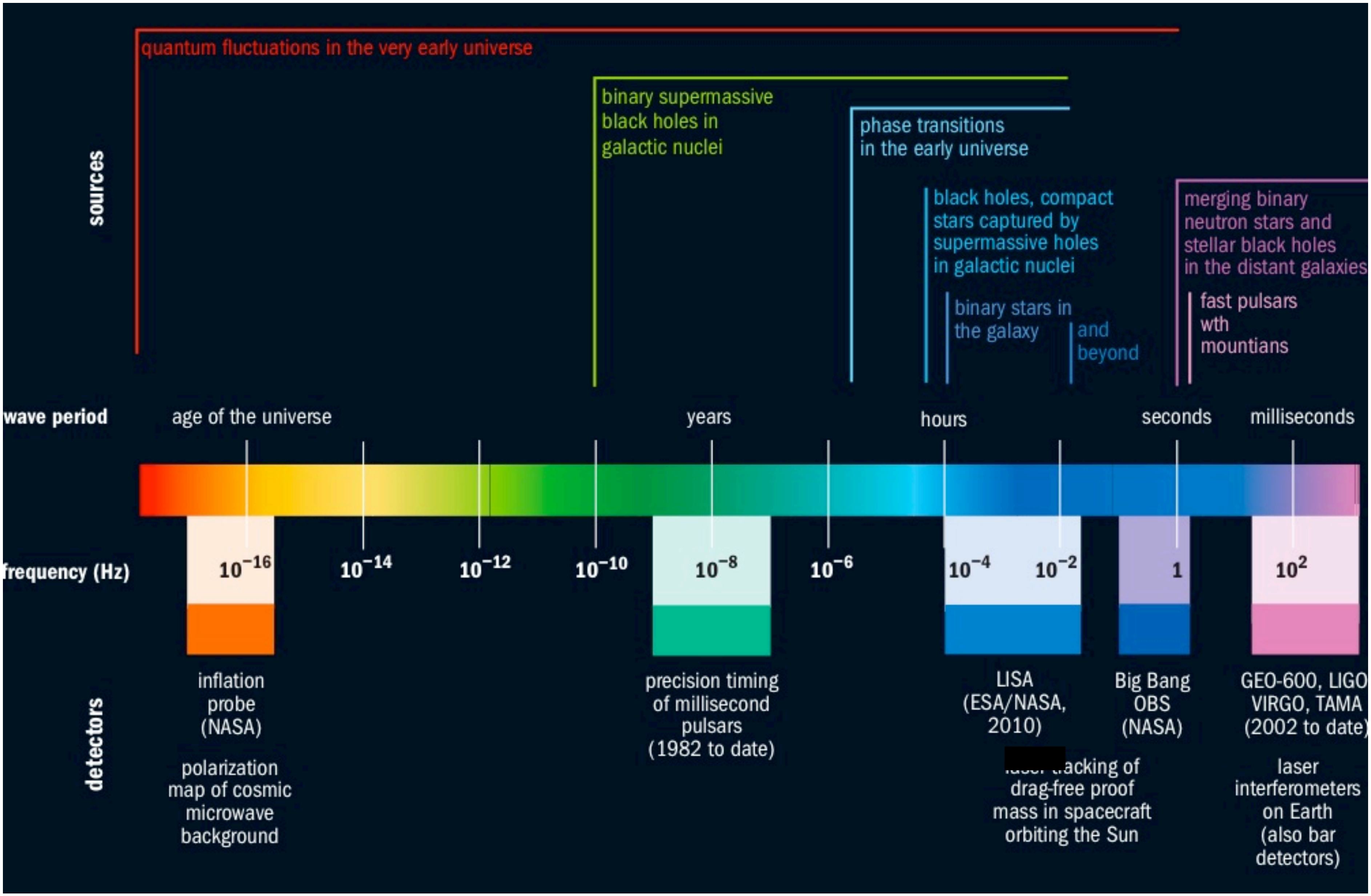
Sensing Spacetime Vibrations

Gravitational Waves are an entirely new way to explore the Universe

- Caused by motions of mass and energy
- Waves penetrate:
  - any matter
  - black holes from the event horizon
  - early universe from singularity
- Waveforms record in precise detail the motion of distant matter
- Frequencies probed by LISA (~0.1 to 100 mHz) are rich in gravitational activity
- LIGO: high frequencies (~100 to 1000 Hz)
- Millisecond pulsar timing: very low $f \sim y^{-1}$

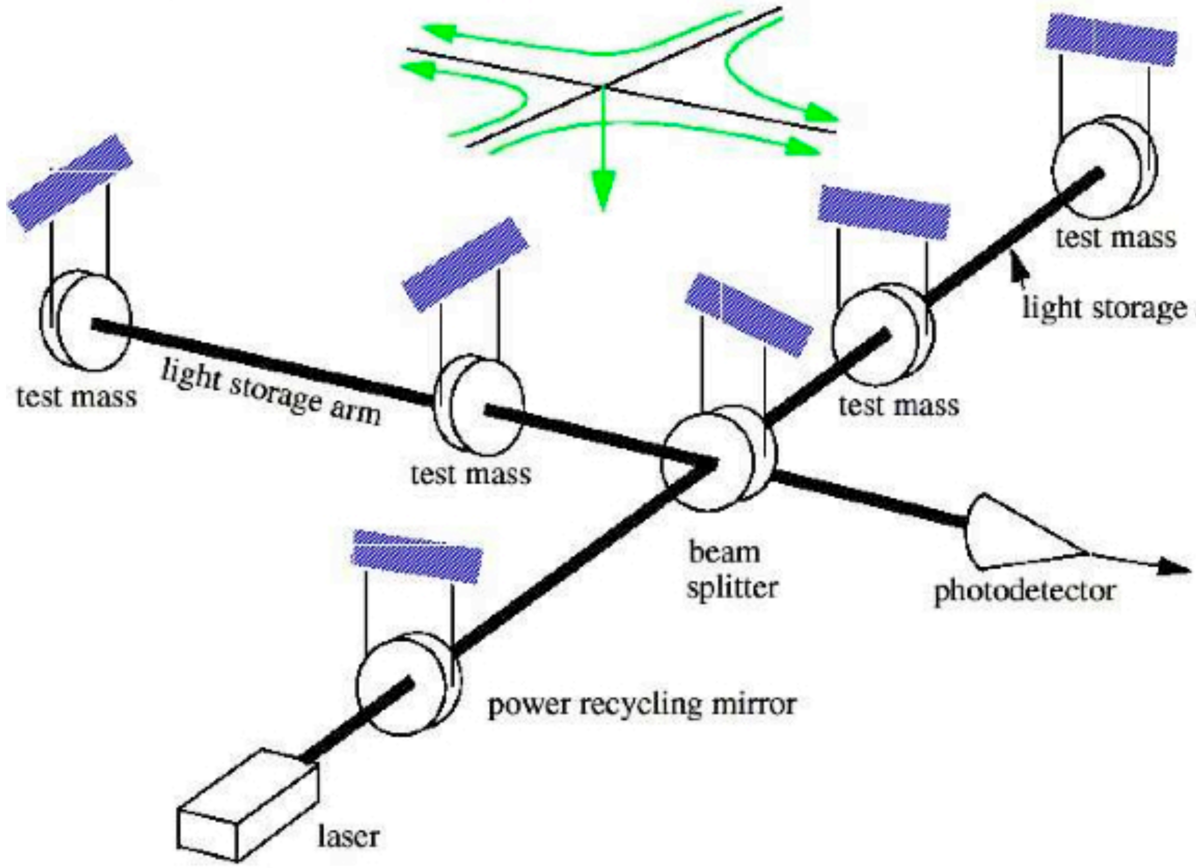


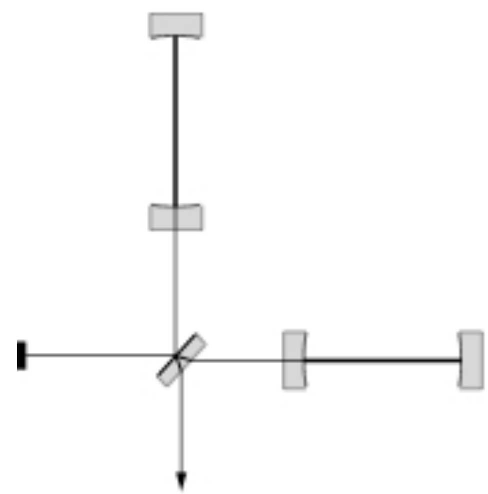
Cosmic Gravitational Wave Spectrum



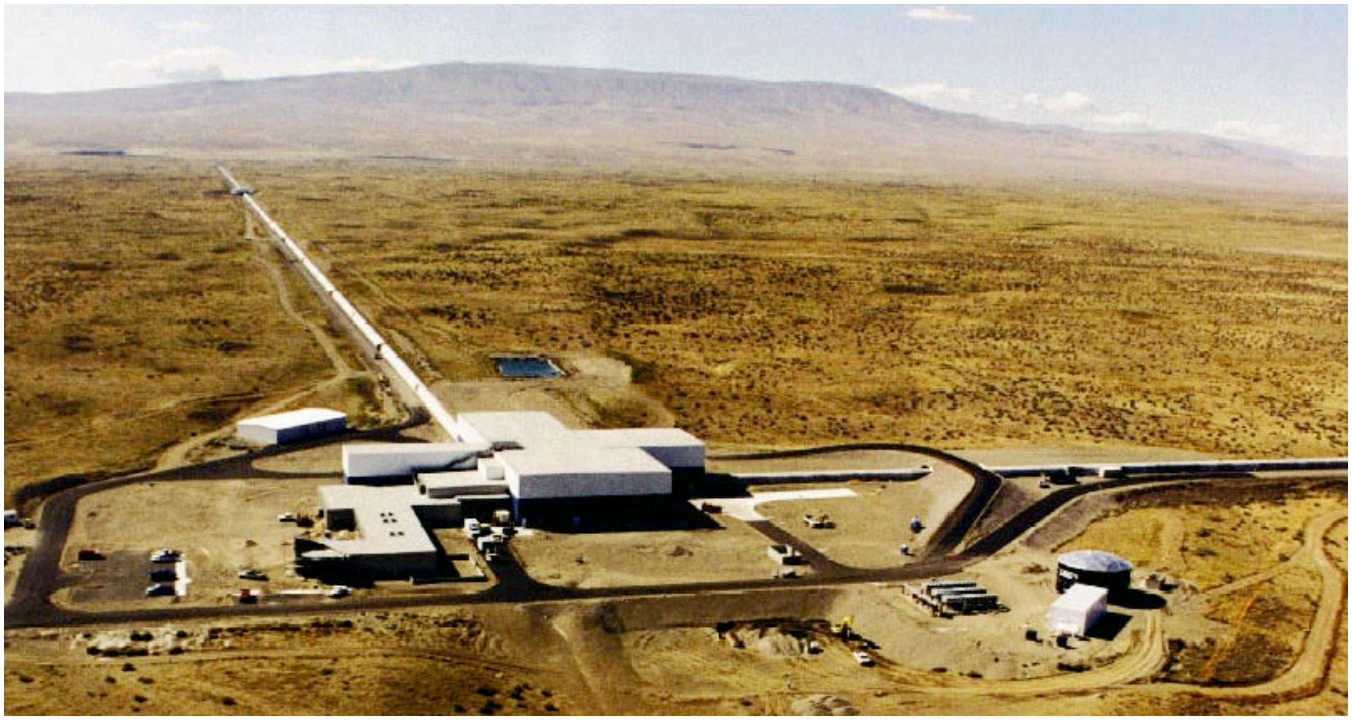
Supersensitive microphones: interferometers

Fig. 1. Schematic layout of a LIGO interferometer.



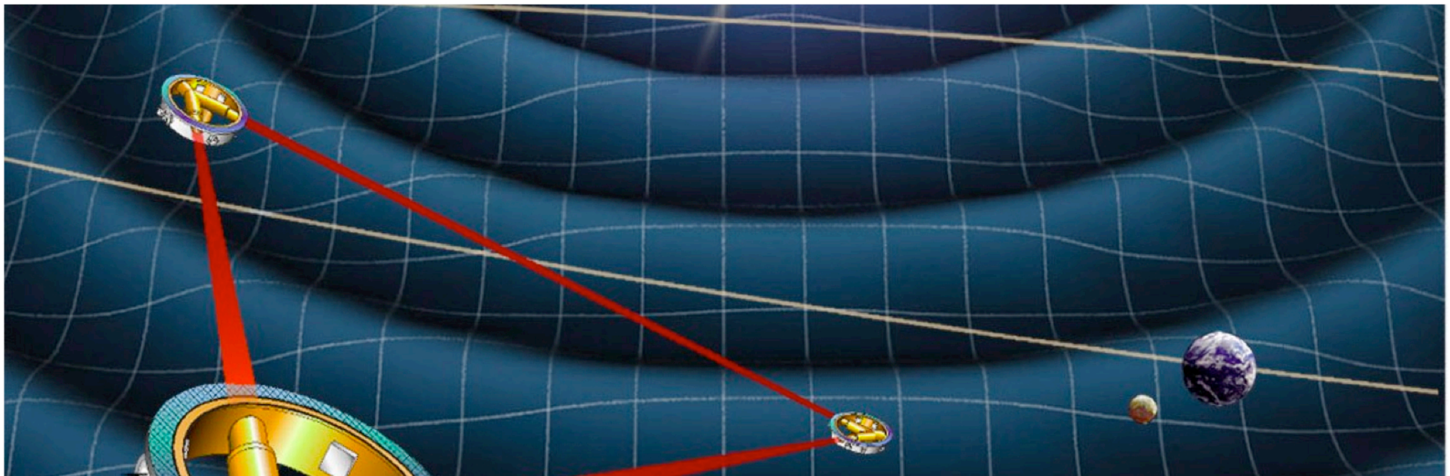


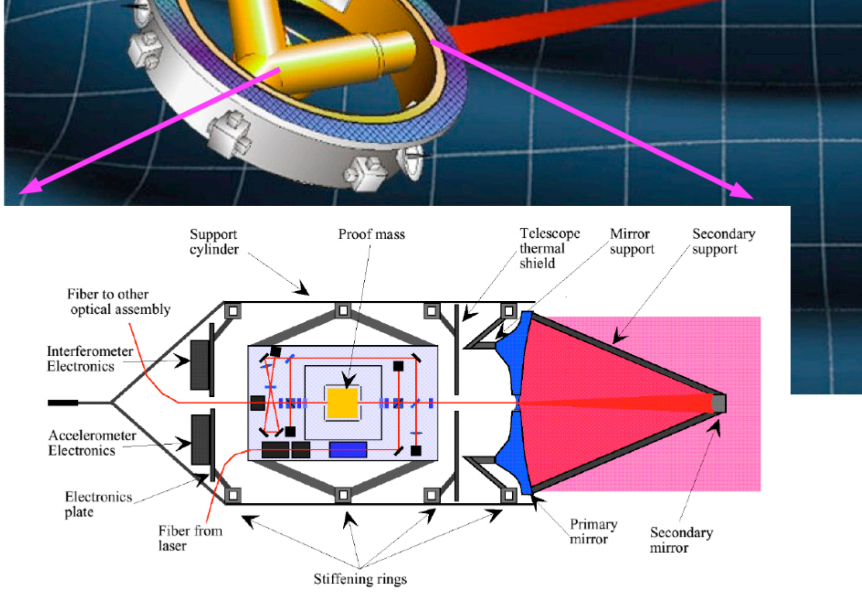
on the ground: high frequencies (10 to 1000 Hz)



Last gasps (minutes) of dying stars:
neutron stars, black holes, supernovae

LISA mission: low frequencies from space





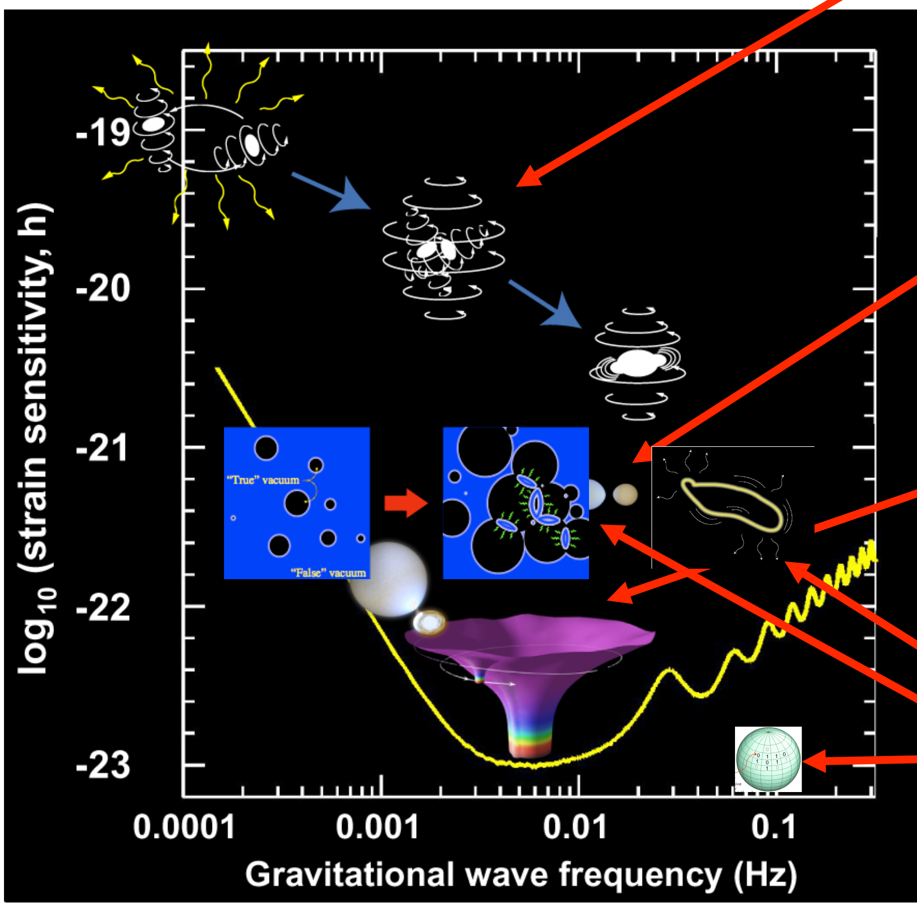
How LISA works:

- 3 spacecraft, orbiting sun
- 5 million km separations
- Two 1.9kg proof masses, two 40cm telescopes, and two phase-locked 1W lasers in each spacecraft.
- NO constellation control. Micronewton thrusters only to keep each s/c following its proof masses and all pointed at each other.
- 5 year mission (limited by component failure, not consumables)

S. Phinney, Texas 2006

Strong Signals in the LISA frequency band

LISA signals record a richly populated universe of strong sources



Massive Black Hole Binary (BHB) inspiral and merger

Ultra-compact binaries

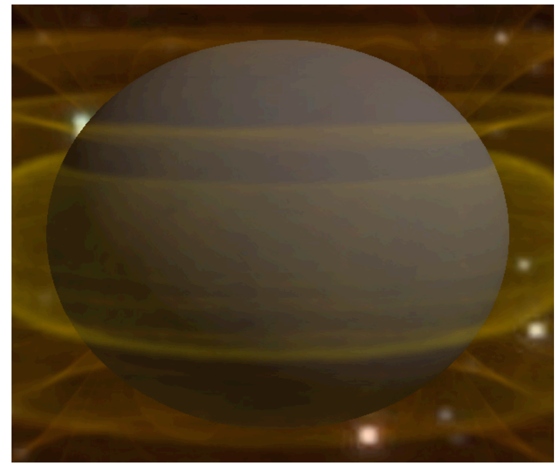
Extreme Mass Ratio Inspiral (EMRI)

Cosmic backgrounds, superstring bursts, holographic uncertainty?

Stationary, isolated Kerr black holes: just mass and spin

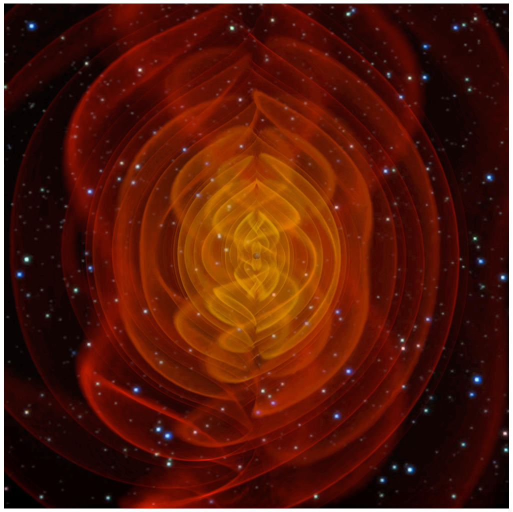
"The black holes of nature are the most perfect macroscopic objects there are in the universe: the only elements in their construction are our concepts of space and time. And since the general theory of Relativity provides only a single unique family of solutions for their descriptions, they are the simplest objects as well."

S. Chandrasekhar, "The Mathematical Theory of Black Holes"



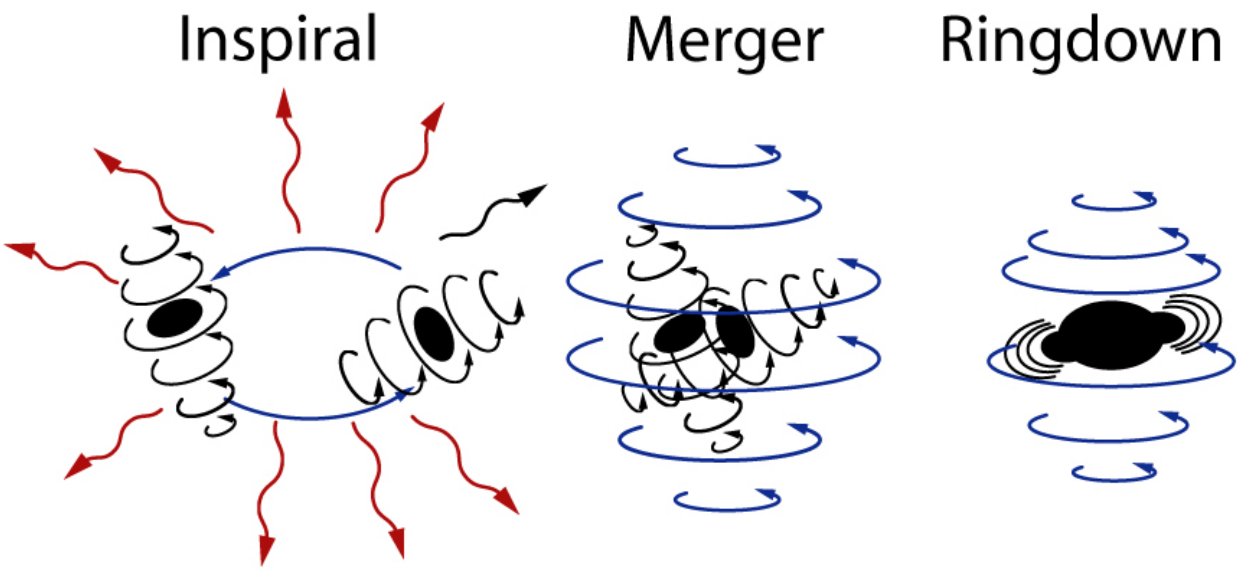
We will understand black holes as well as atoms

Strong signals from binary black hole mergers, and a complete mathematical description including all degrees of freedom, will make them the first precisely and completely characterized macroscopic systems



Black Hole Binaries: cataclysms of pure vacuum spacetime

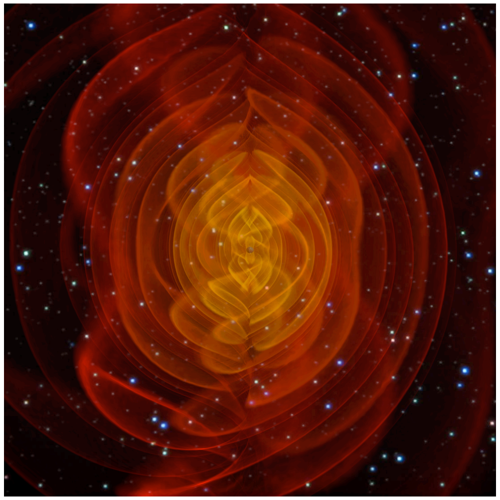
Signals from inspiral, merger and ringdown of massive binary black holes test General Relativity's most violent dynamical behavior



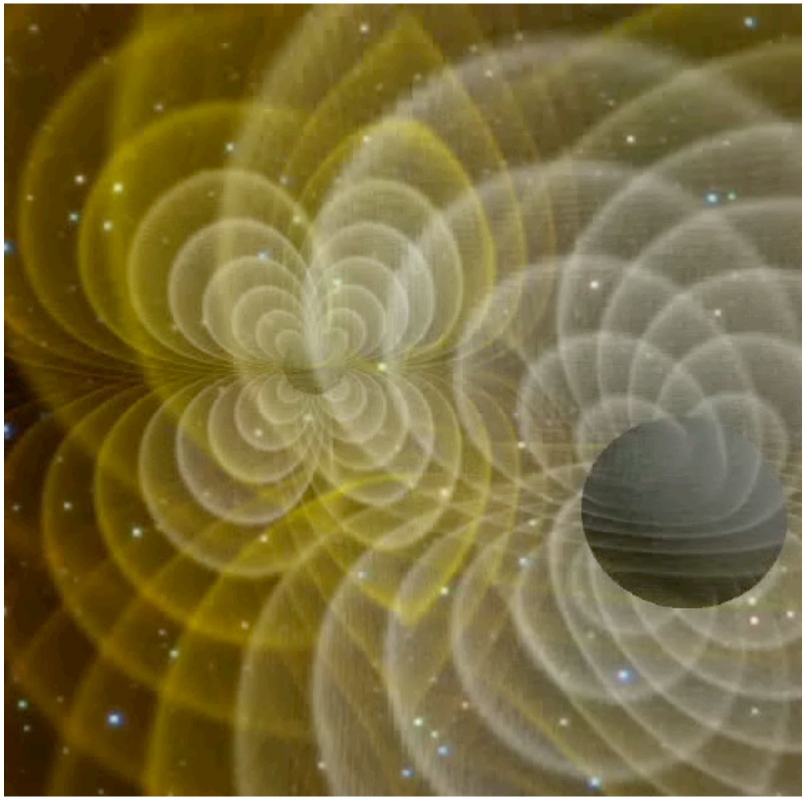
- Waves give precision better than 1% on all black hole parameters: masses, spins, orbits, direction, distance
- dynamics of pure spacetime interacting with itself
- Huge power: ~10^{49} watts, ~10^{23} suns during single merger

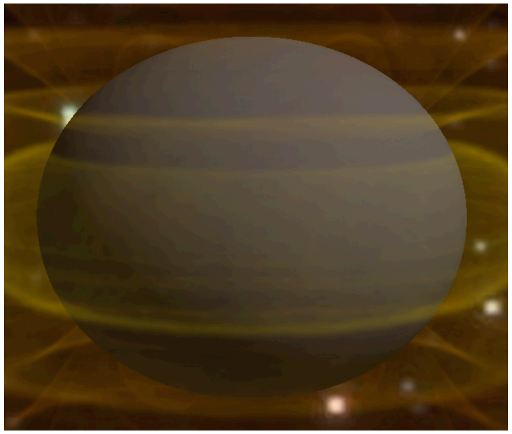
Dynamical Spacetime

Numerical tools are in hand to interpret LISA data using General Relativity in extreme spacetimes



Red shows gravitational radiation



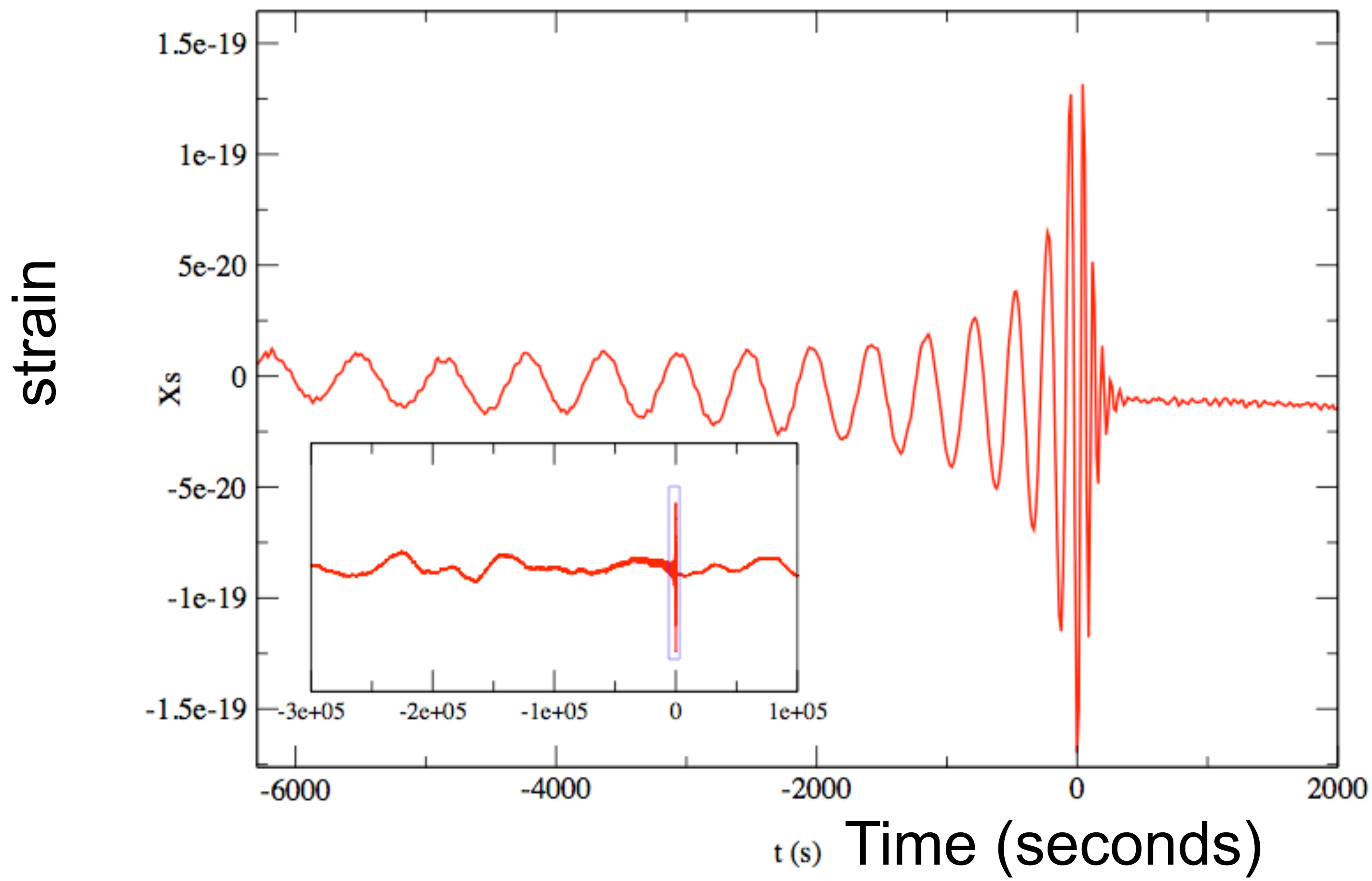


(computation NASA/GSFC,visualization NASA/Ames)

Signal from black hole merger event

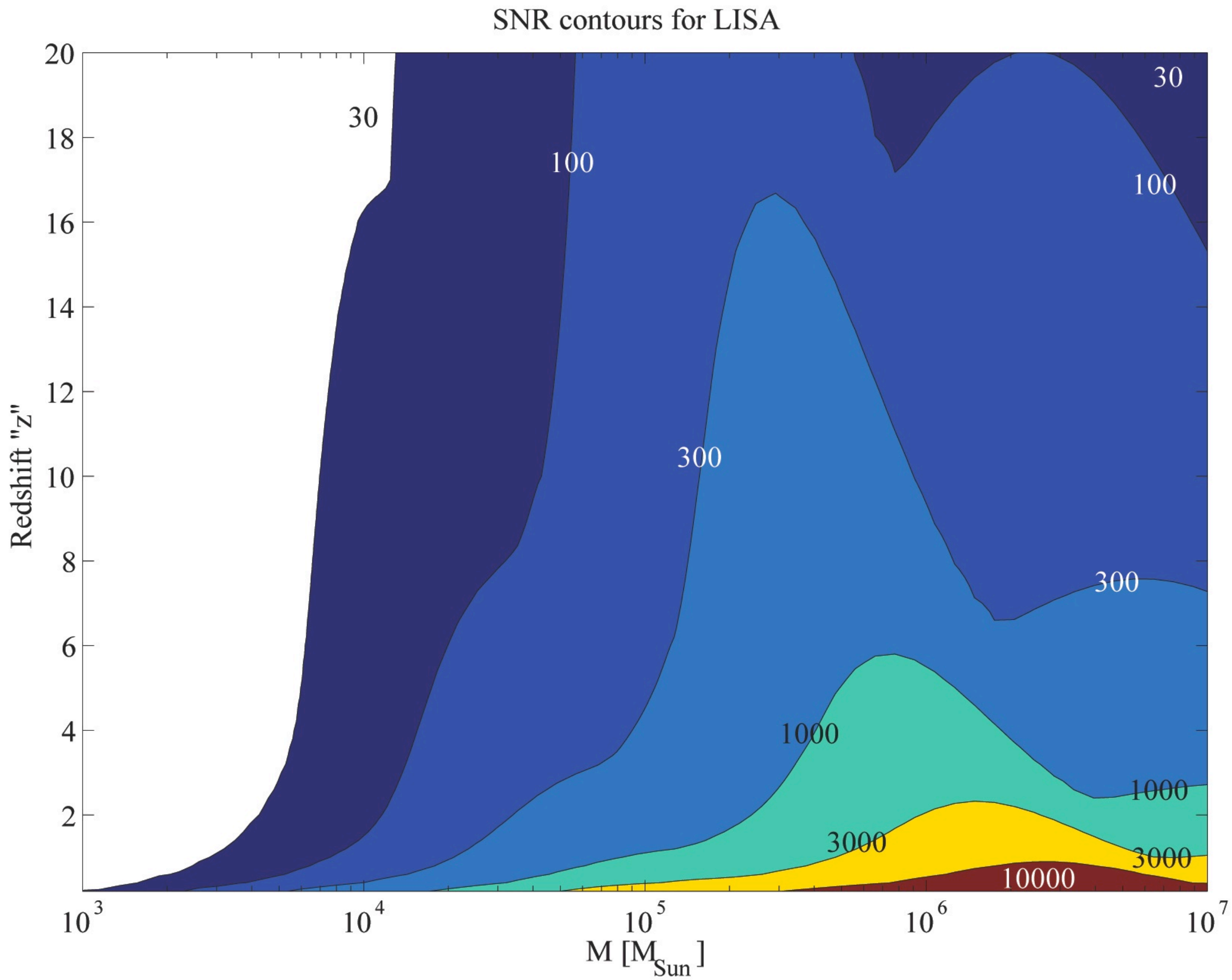
Merger signals have high SNR even in a single wave cycle

Simulated LISA datastream:
two $10^5 M_\odot$ BH at z=5, simulated noise (S/N~500)



Massive Binary Black Holes: strong signals

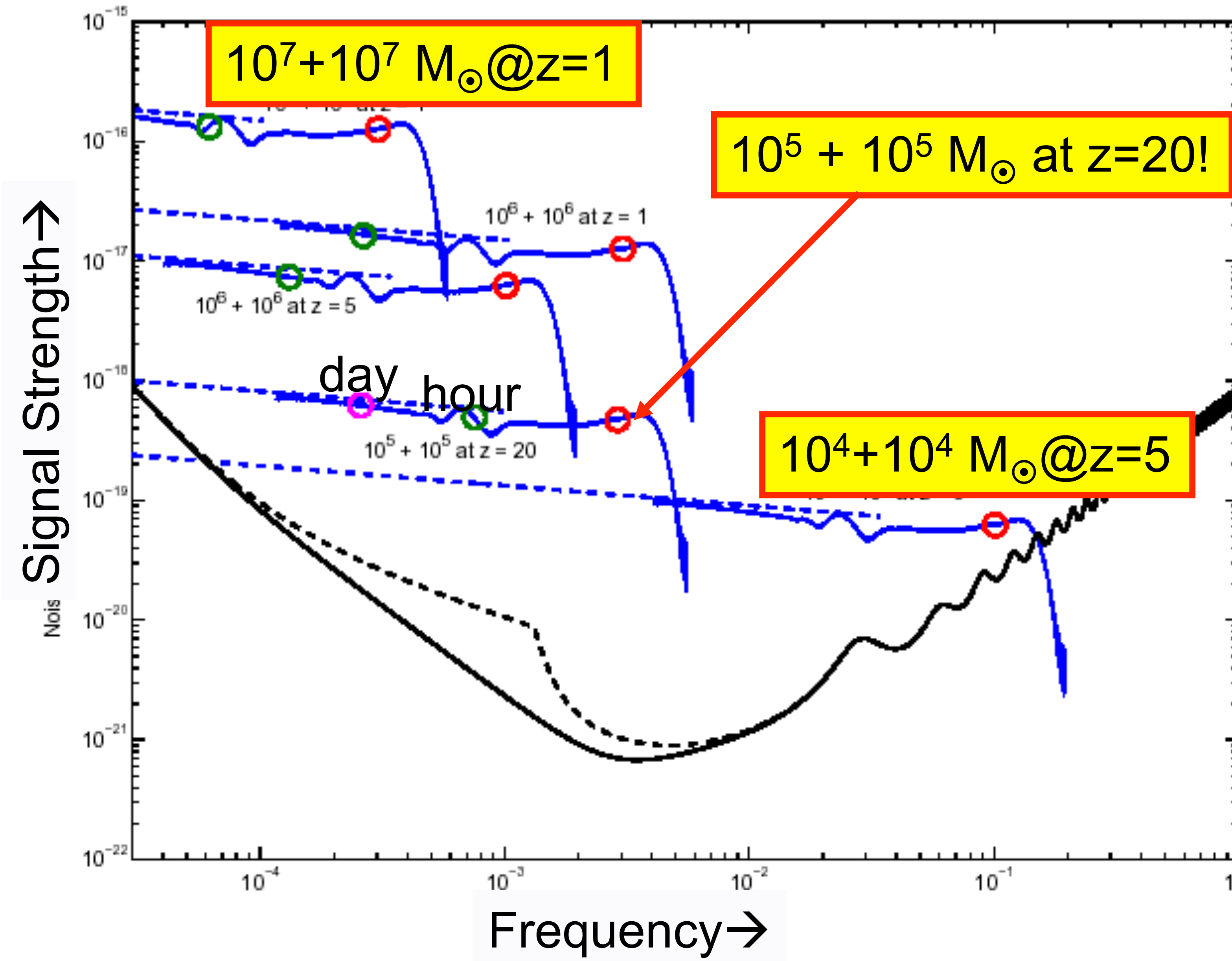
Contours of SNR, equal mass merger (optimal)



Redshift→

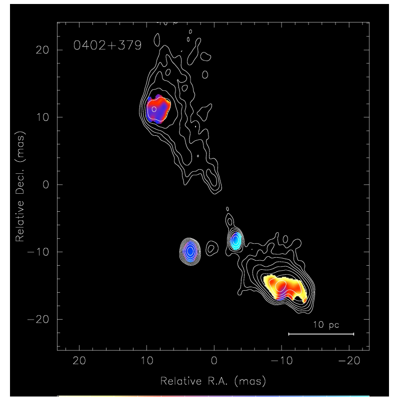
Mass→

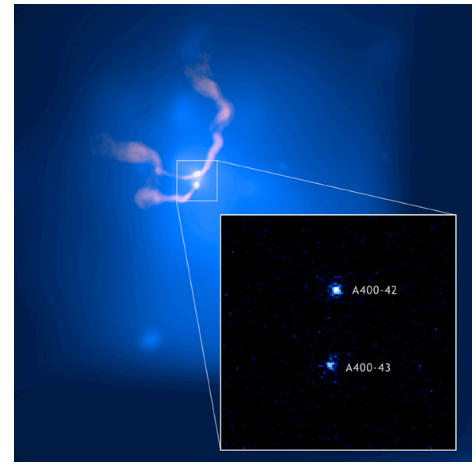
Massive Binary Black Holes: signal evolution

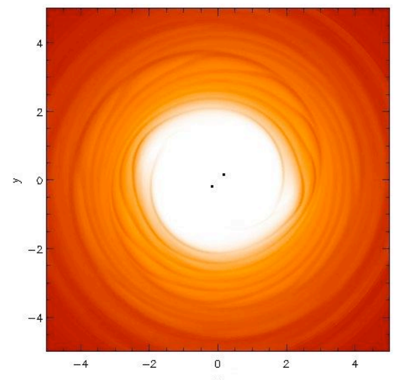


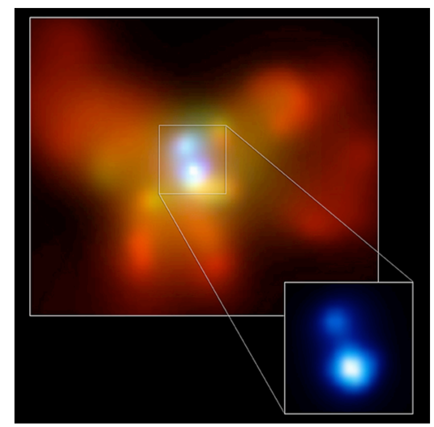
Visible signals from gravitational wave sources

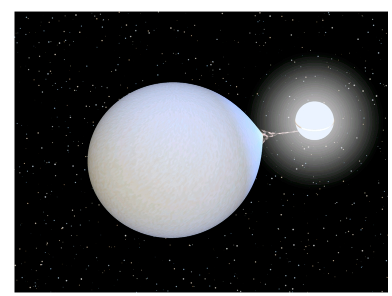
LISA sources have possible electromagnetic counterparts over a wide variety of wavebands and timescales: an exploratory bonanza for wide field synoptic imaging and spectroscopy





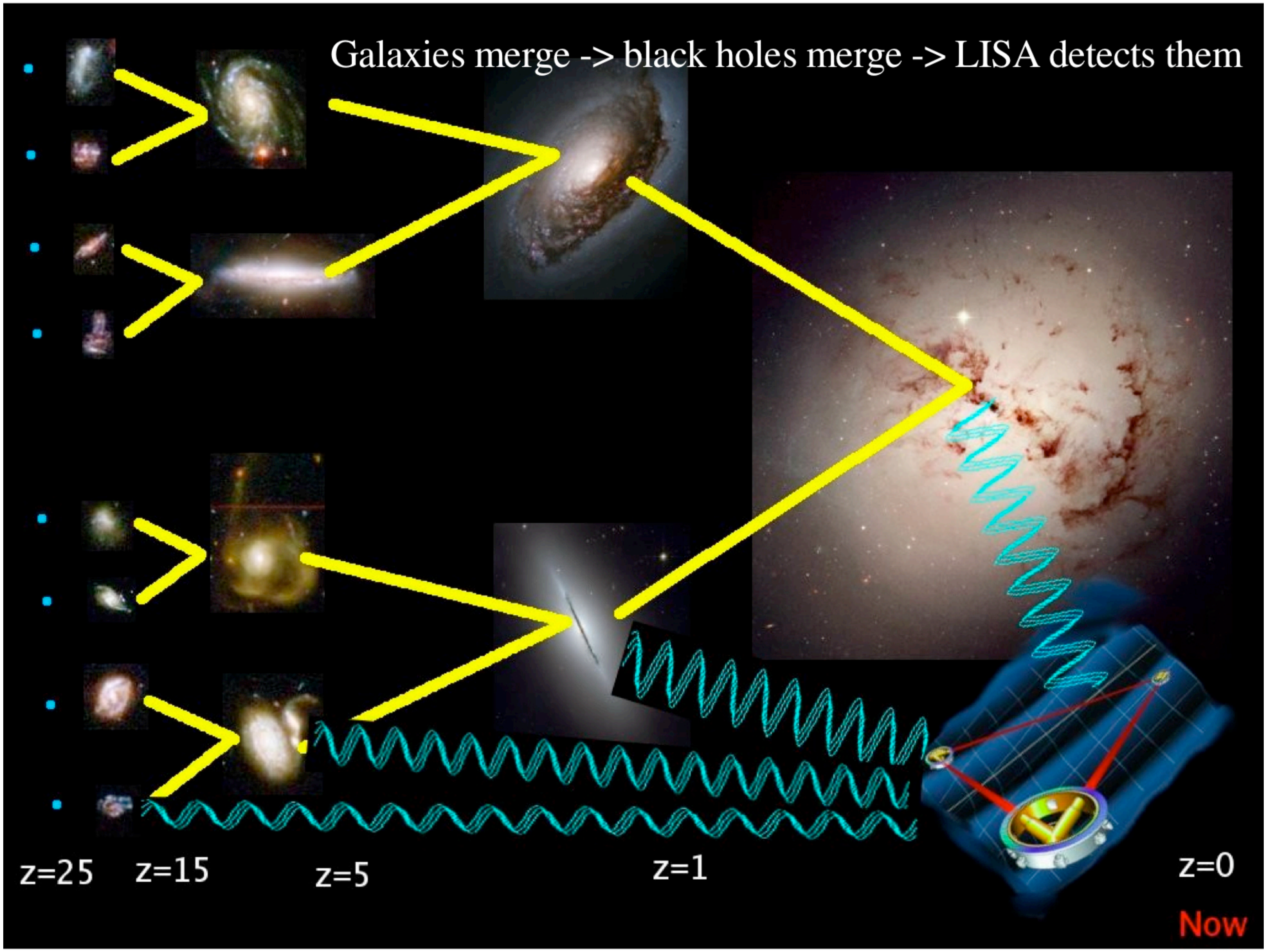






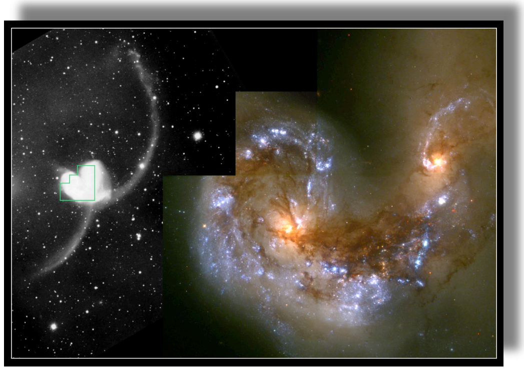
- Black-hole mergers in real time
  - Months to weeks notice within 1°
  - Last day: position to ~15 arcminutes
- Precursor, prompt and afterglow emission from gas around black hole mergers: radio to X-rays
- Host galaxies: nuclear starbursts, AGN
- Tidally heated, eclipsing and accreting white dwarf binaries (several known already)

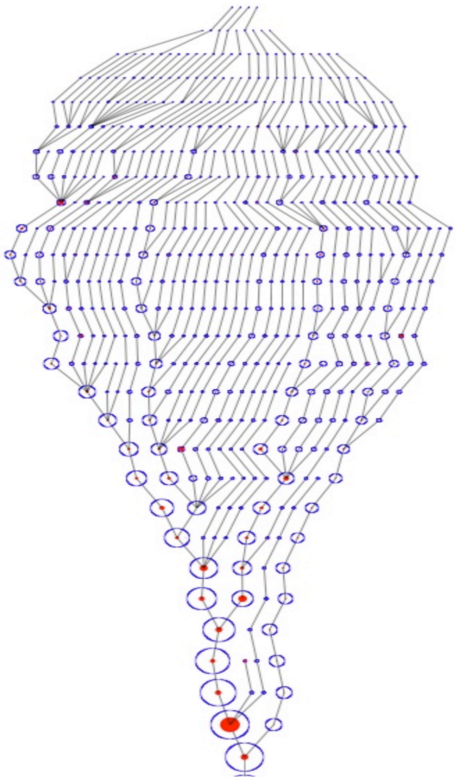
History of massive black hole mergers



LISA directly observes growth of massive black holes

BH mergers at high redshift record in detail the history of galaxy formation and nuclear evolution

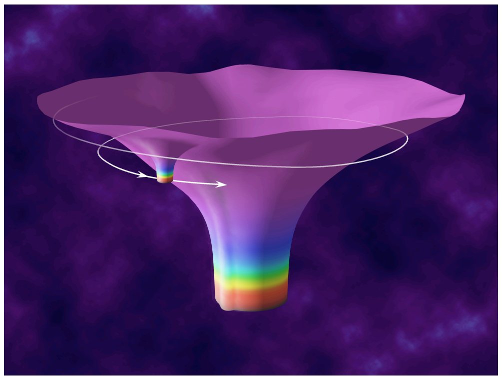


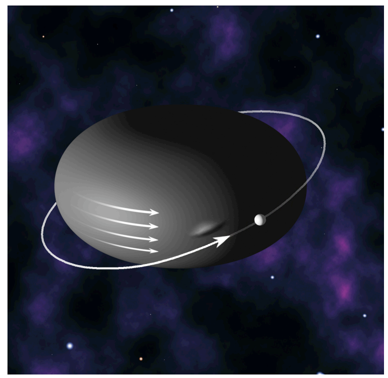


- ΛCDM cosmology predicts 100’s to 1000’s of LISA black hole merger events
- Merger events record seed masses, growth/merger history, mass and spin since z=20

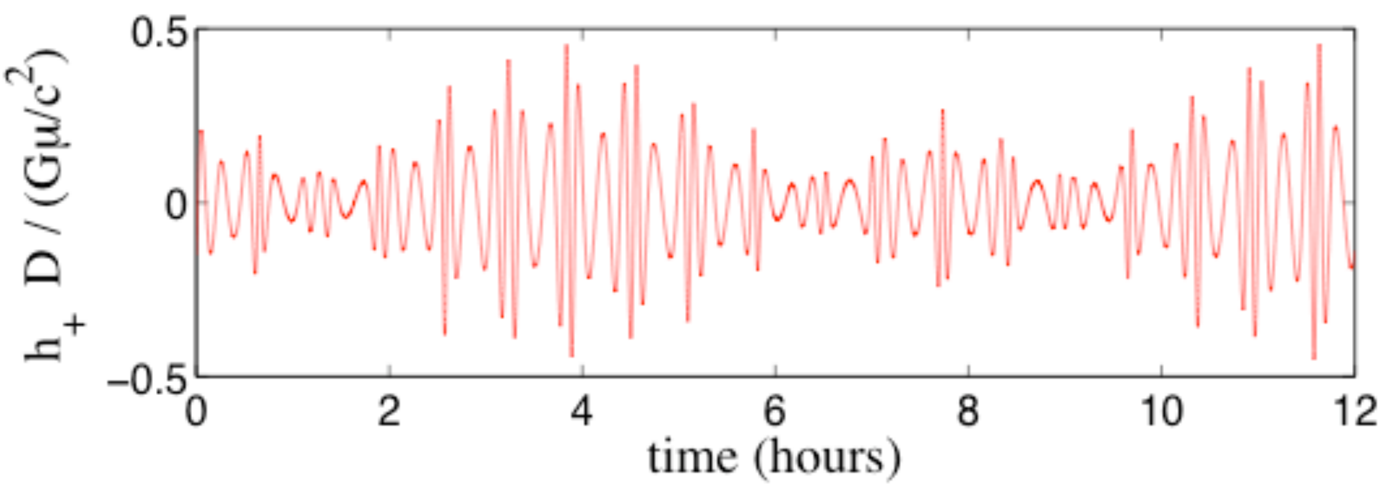
How well does General Relativity describe real black holes?

Waveforms of Extreme Mass Ratio Inspirals (EMRIs) test the unique Kerr black hole solutions of GR





- ~10^5 orbits
- Rich waveforms test:
  - "No-hair Theorem" of General Relativity to ~0.01% accuracy
  - Response of dynamical tide on horizon to ~1%



Sounds of two holes merging

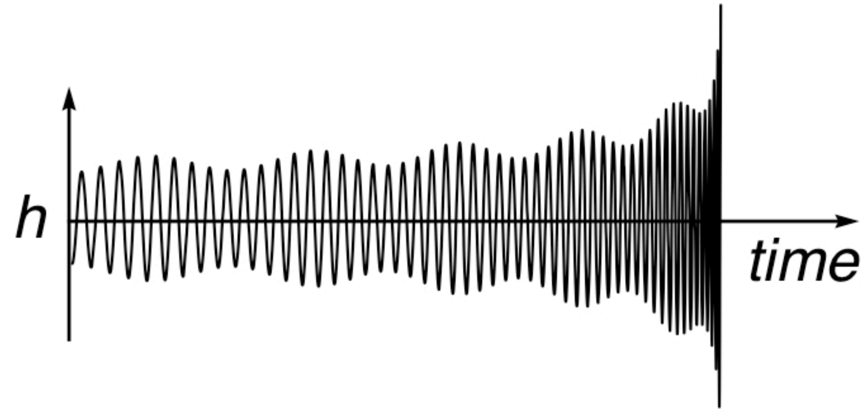
- Initially eccentric EMRI orbit, falling into a spinning hole

- Circular EMRI orbit, slowly spinning massive hole

S. Hughes

Absolute Distances from LISA Waveforms

Waveforms of black hole binaries give precise, gravitationally calibrated distances to high redshift



Absolute luminosity distances can be derived *directly* from

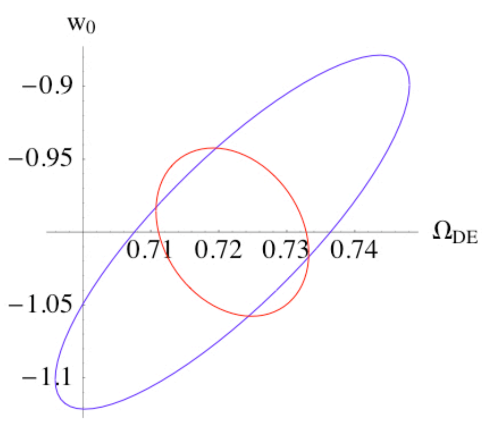
– amplitude (ratio of size to distance)

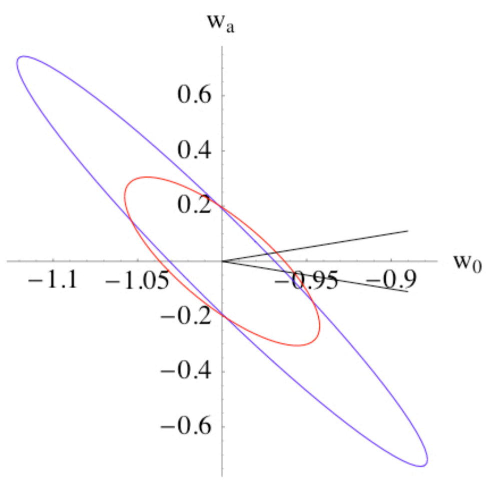
– orbital frequency, chirp time (absolute size)

- Distances accurate to ~1% per event
- Absolute calibration using only gravity

Absolute Distances: Hubble Constant and Dark Energy

- 100's of events
- Cosmological test requires (independent) redshift of host
- Noise from weak lensing at $z>1$
- Comparable precision to other techniques
- ***Absolute*** **&** ***Independent*** **measurement**

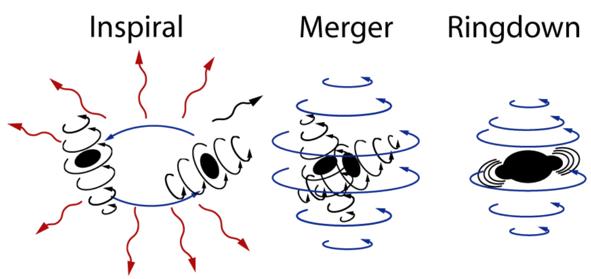


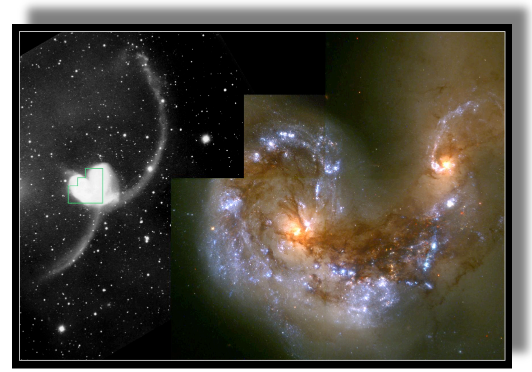


H_0 and Dark Energy parameters potentially measured to <1%

50 absolute and relative distances at 1%, Planck prior, five unfixed parameters assumed. (M. Kerr)

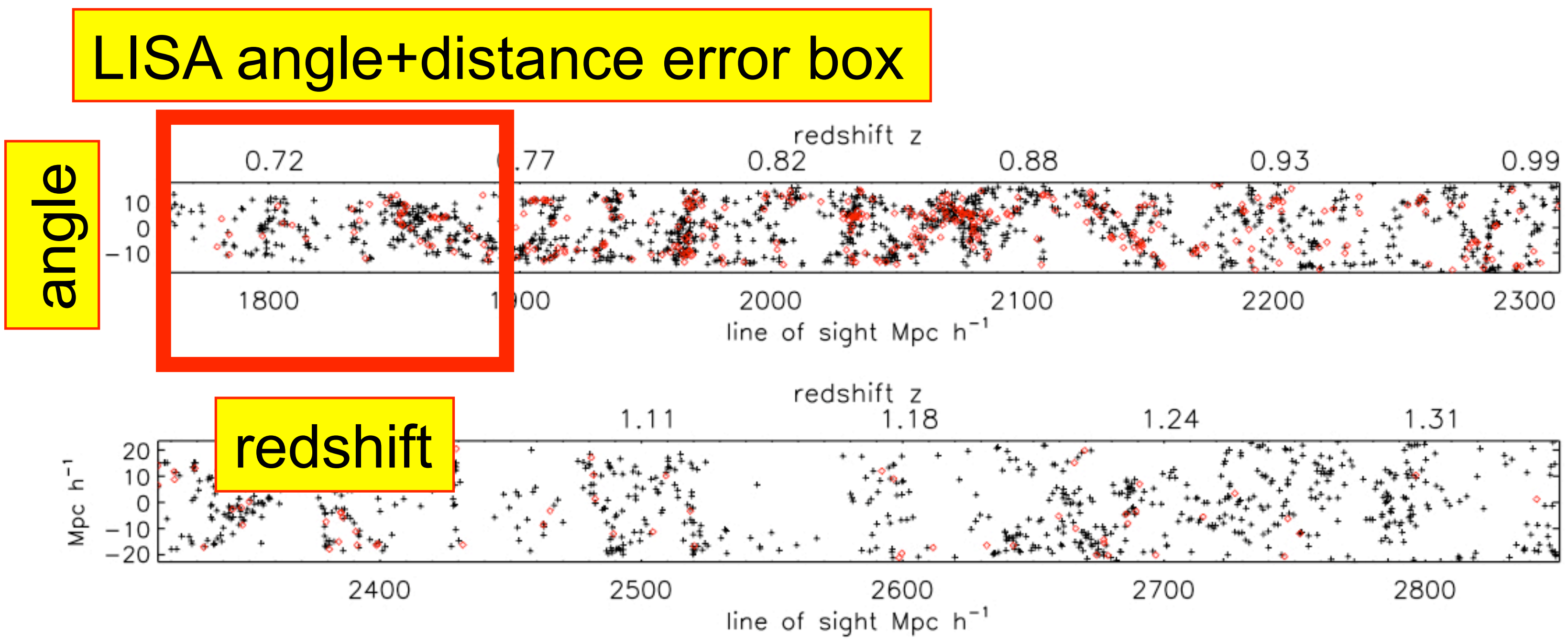
Redshifts from electromagnetic counterparts





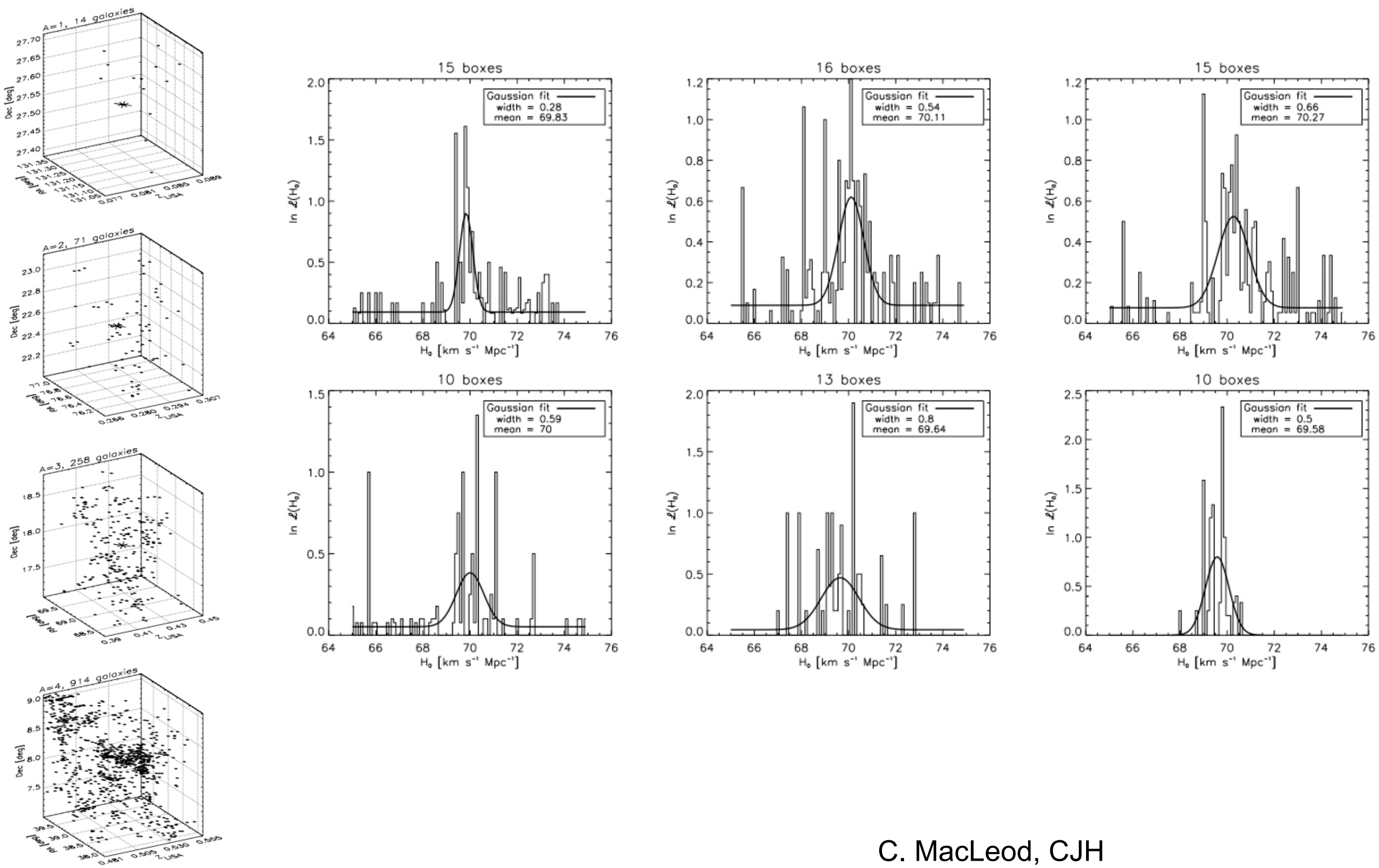
Statistical redshifts for precision cosmology

- Galaxies are highly clustered: "cosmic web"
- Redshift surveys in LISA error boxes can yield z information statistically without identification of individual hosts



Statistical Redshift Information without host IDs

- galaxies "vote" on the Hubble constant

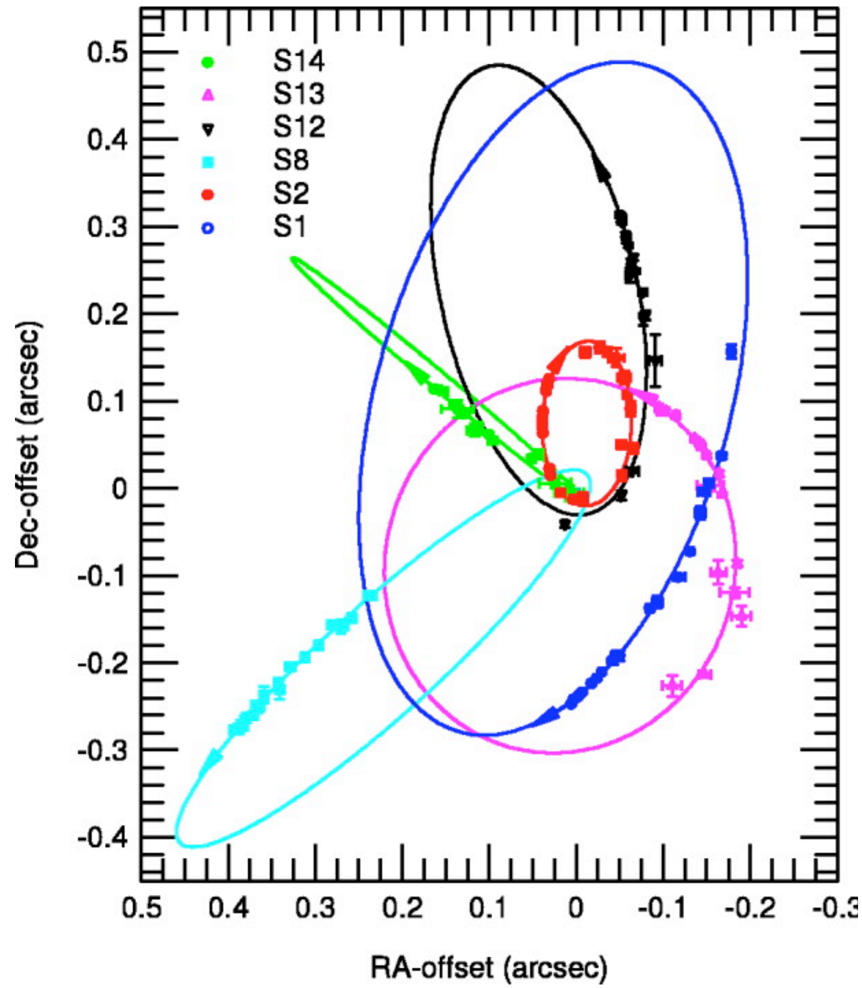


C. MacLeod, CJH

Galaxy nuclei: Massive Black Holes and What Else?

LISA will reveal the rich astrophysics of stellar populations interacting with central black holes

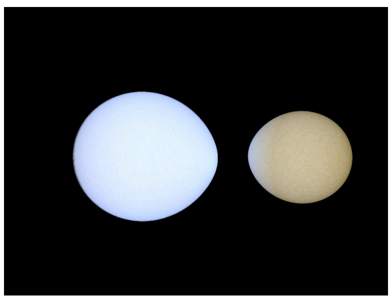
- ordinary stars, black holes, neutron stars, white dwarfs, brown dwarfs captured and swallowed
- Waves emitted during MBH banquet
- Spins of BHs measure angular momentum history

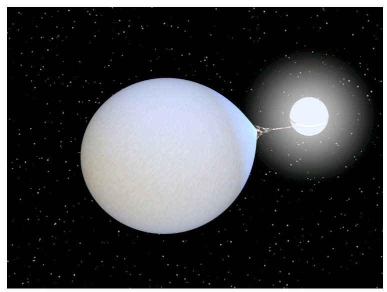


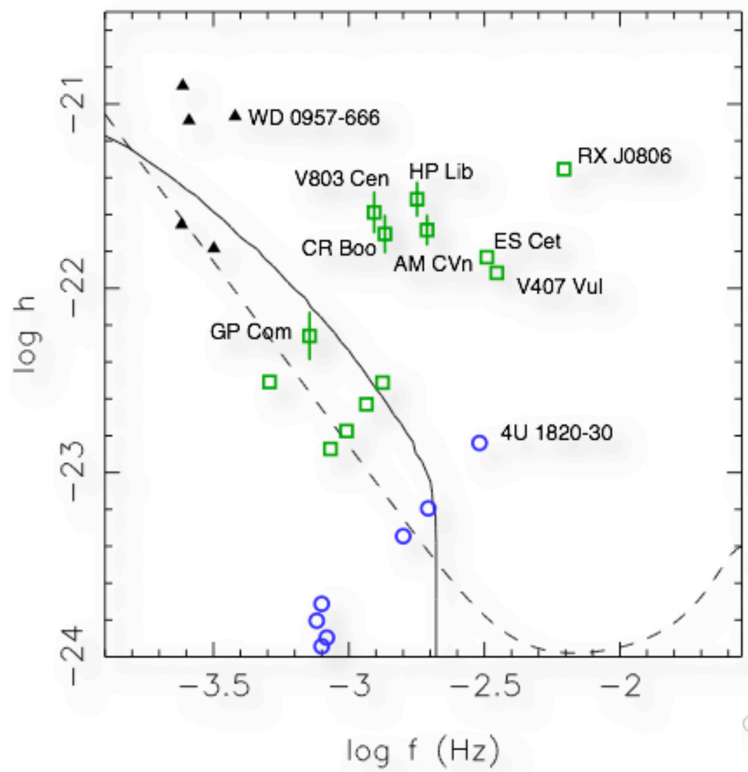
MBH in Milky Way

Exploring a new Galaxy of compact binary stars

LISA will measure orbital motions and 3D positions throughout our Galaxy of binary stars at the extreme endpoints of their evolution

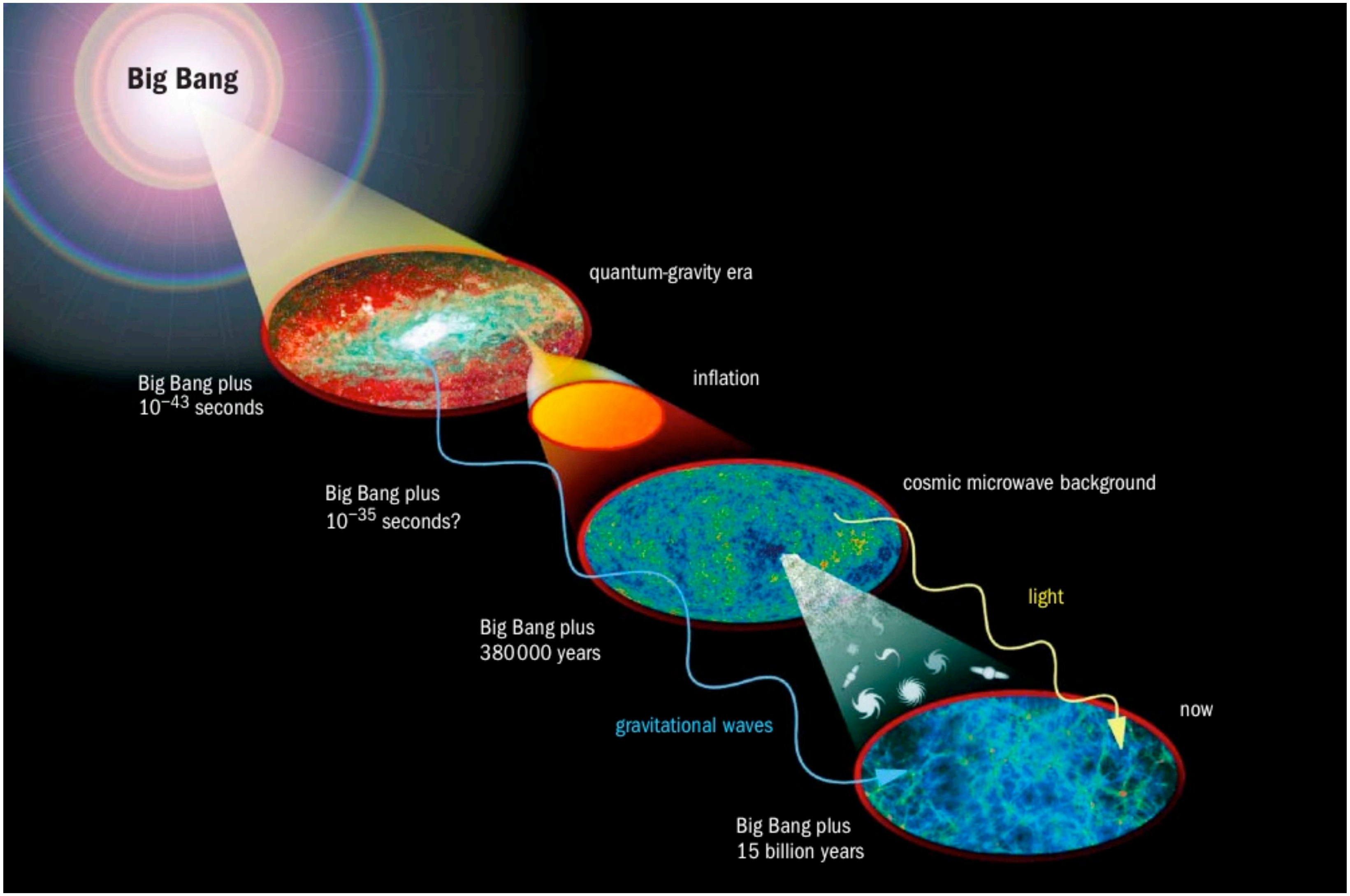






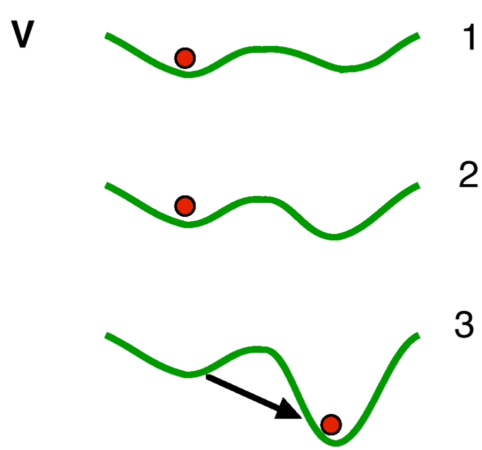
- ~10 known binaries are guaranteed “verification sources”
- ~10,000 more will be individually detected
- Millions contribute to low frequency confusion background
- Extreme degenerate stars (mainly white dwarfs, some NS, BH)
- Precursors of Type Ia SNe, millisecond pulsars, exotic novae

Gravitational Waves from the Early Universe



How loud was the Big Bang?

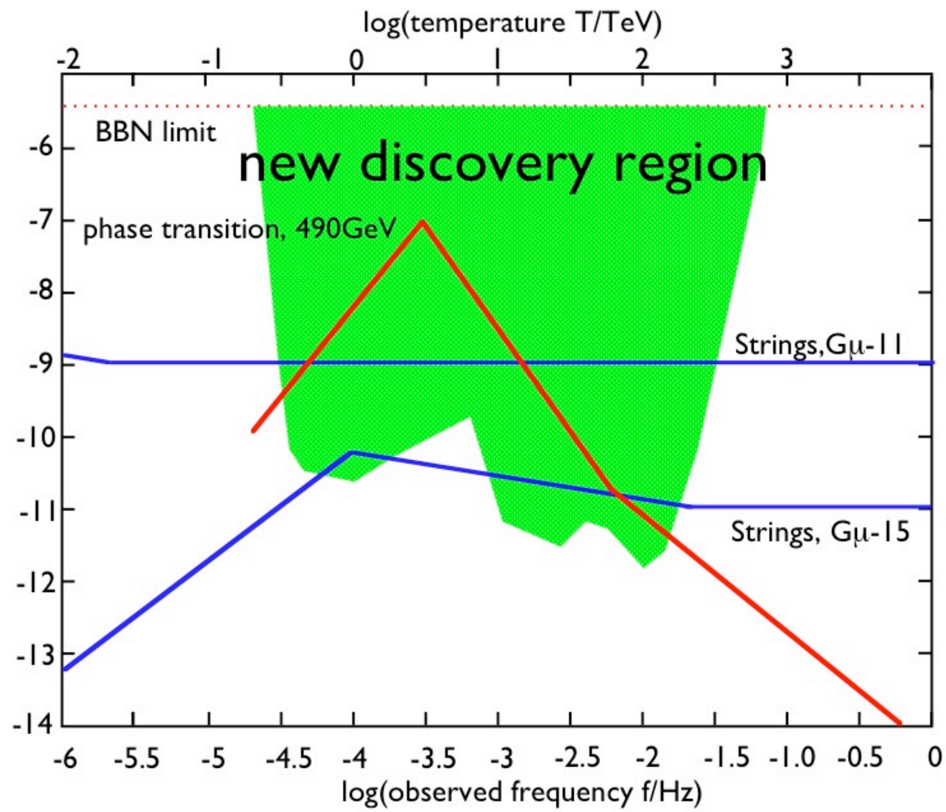
- Phase transition: vacuum free energy thermalizes via explosive nucleation and turbulent cascade
- Free energy converts into ~horizon-scale bulk flows
- Gravitational waves survive
- In LISA band for ~terascale reheat temperature
- LISA senses the roar of terascale cataclysms



CJH, Physics World, June 2007

Sensitivity of LISA to phase transition backgrounds

LISA frequencies span critical temperatures from ~ 0.1 to 1000 TeV



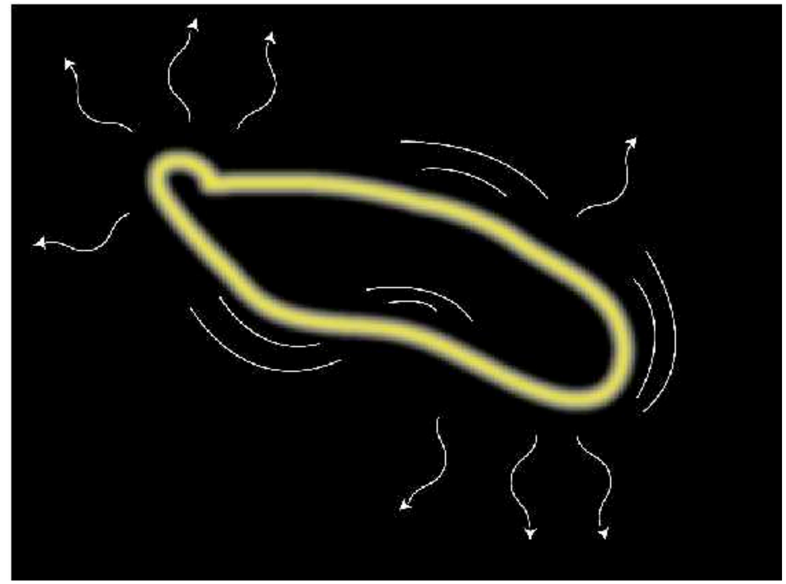
$\mathrm{Log}(\, \Omega_{GW} \,)$

Log (frequency)

GW production efficiency as small as ~10^{-7}

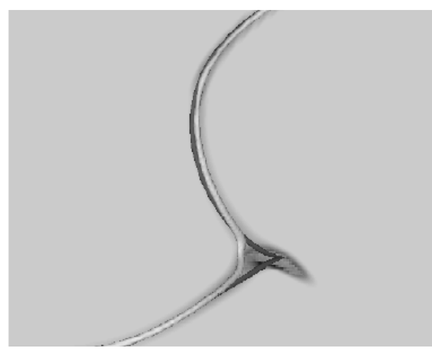
Cosmic superstrings

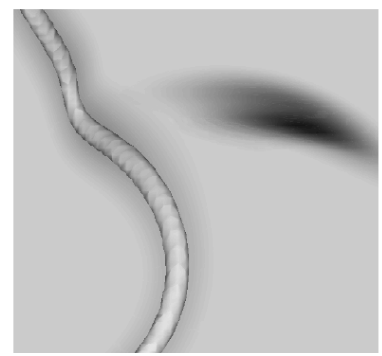
- New form of energy: flux tubes (fields), 1-branes (strings)
- Formed after inflation, stretched by cosmic expansion
- Main observable effect is gravitational wave backgrounds from decaying loops



Gravitational waves probe cosmic superstrings

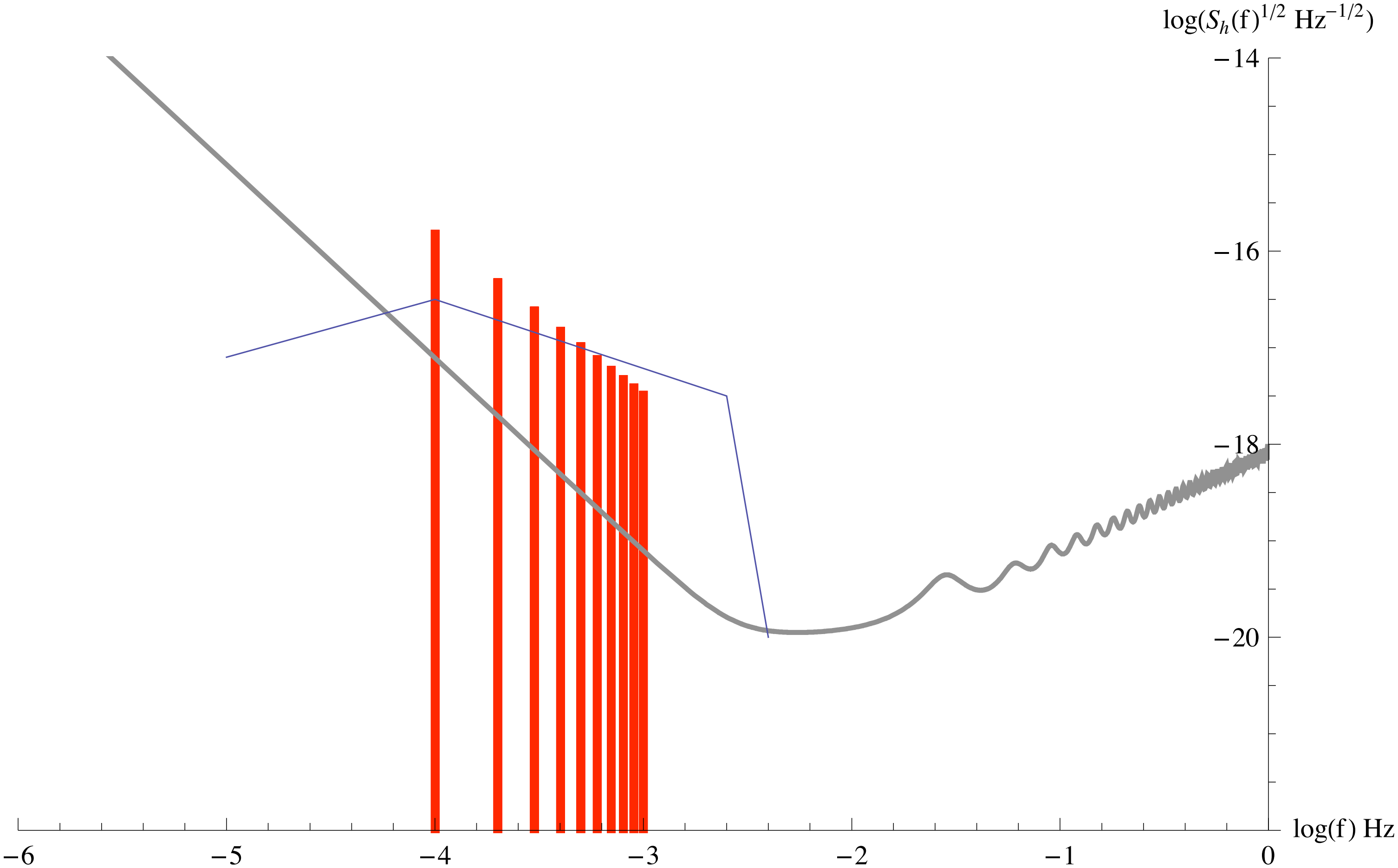
- Millisecond pulsar timing constrains string mass
- LISA will probe very light strings
- Occasional rare bursts from cusps may beam in our direction
- LISA can resolve fundamental tones and overtones from nearby individual string loops in our Galaxy





Cosmic string loops: perfect harmonics

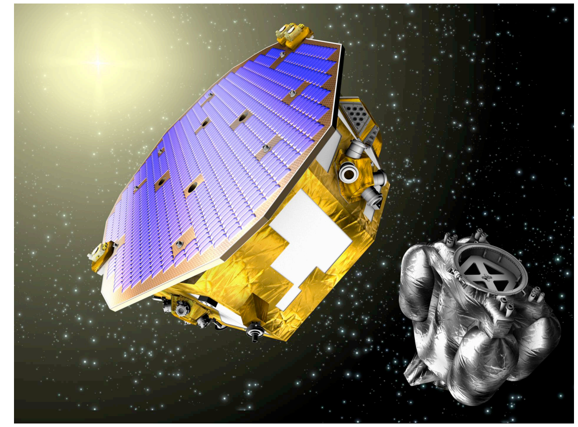
Loop spectrum: like a plucked violin string

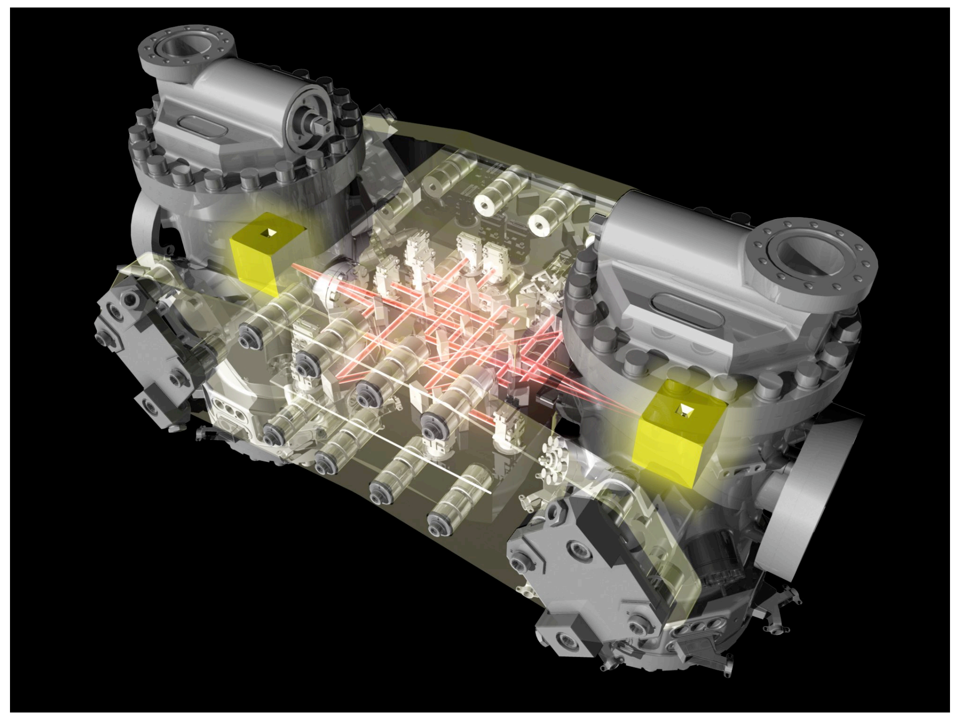


M DePies, UW

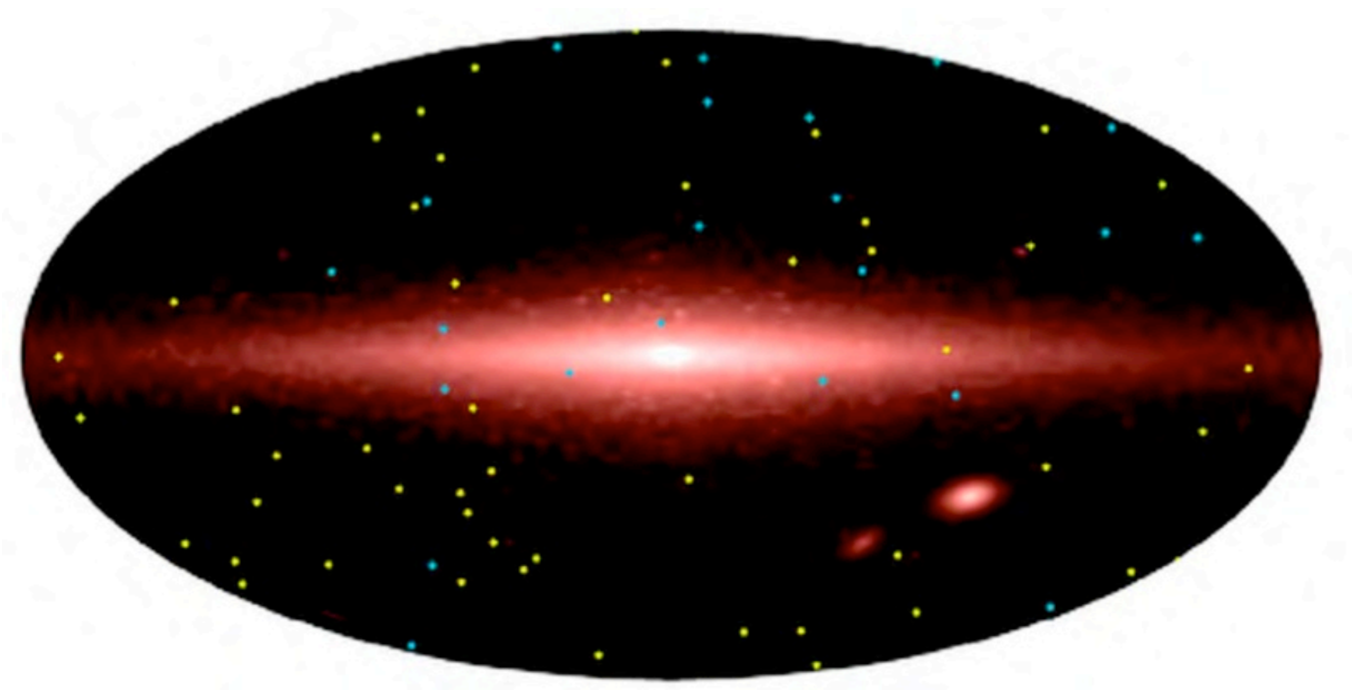
When will LISA fly?

- Idea is ~30 years old
- Design stable for last ~10 years
- Highest science ranking by NRC Beyond Einstein Program Assessment
- Technologically new, risky
- LISA Pathfinder: technology test satellite to launch in 2010
- **LISA needs top ranking in NRC Astro2010 Survey**





LISA will sense the Universe in an entirely new way, and will explore new things that can be explored in no other way



LISA "sky"

Paradoxes of “Empty Space”

- Empty space is not empty
  - Black holes are made of pure spacetime
  - Quantum fluctuations are everywhere
  - Dark Energy: most cosmic energy is in the vacuum
  - Gravitational waves carry energy everywhere
- Empty space is not even really space
  - Space and time are intertwined
- Is there a smallest interval of time and space?
- To study empty space, study empty space

Are time and space infinitely smooth?

- Einstein’s theory assumes spacetime is a classical manifold, infinitely divisible
- This may be just an approximate behavior
- Can we measure the minimum interval of time?

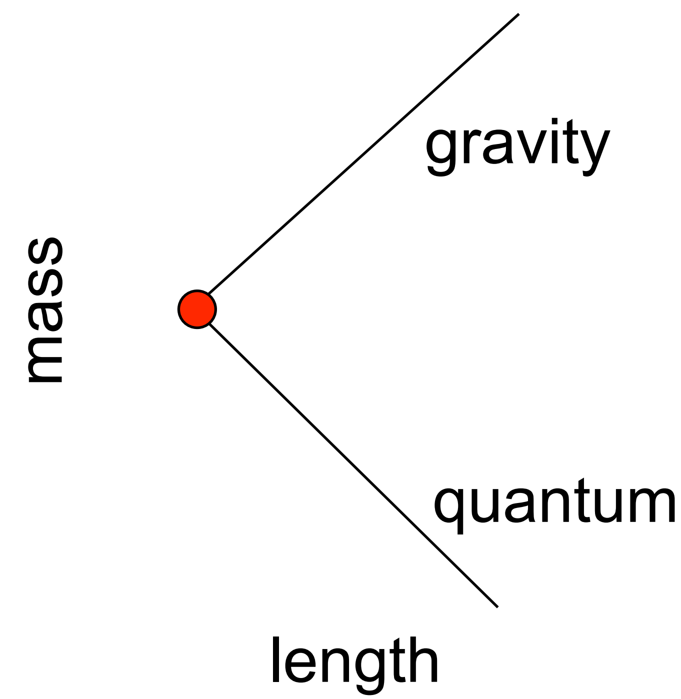
The smallest interval of time

- Quantum gravity suggests a minimum (Planck) time,

$$t_P \equiv l_P/c \equiv \sqrt{\hbar G_N/c^5} = 5 \times 10^{-44} \quad \text{seconds}$$

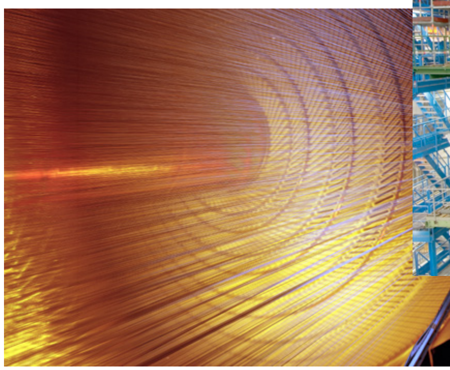
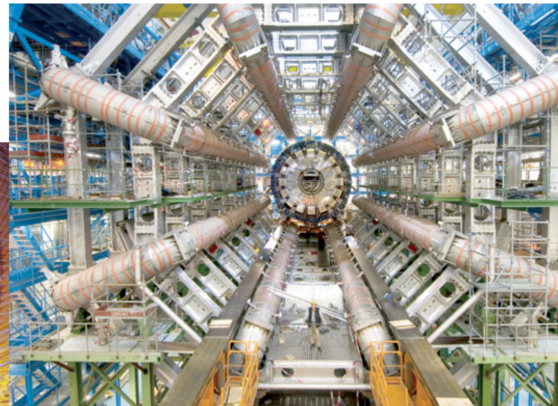
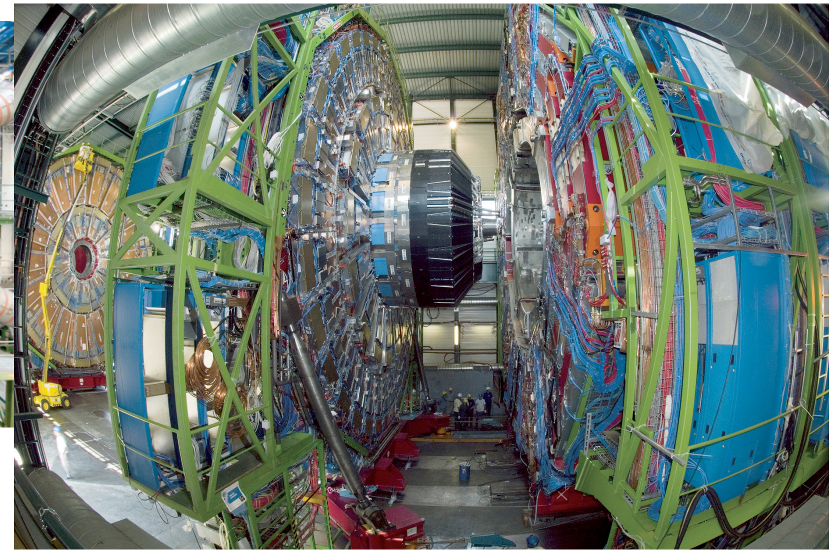
$$l_P = \sqrt{\hbar G_N/c^3} = 1.616 \times 10^{-33}\mathrm{cm}$$

- ~ particle energy 10^{16} TeV

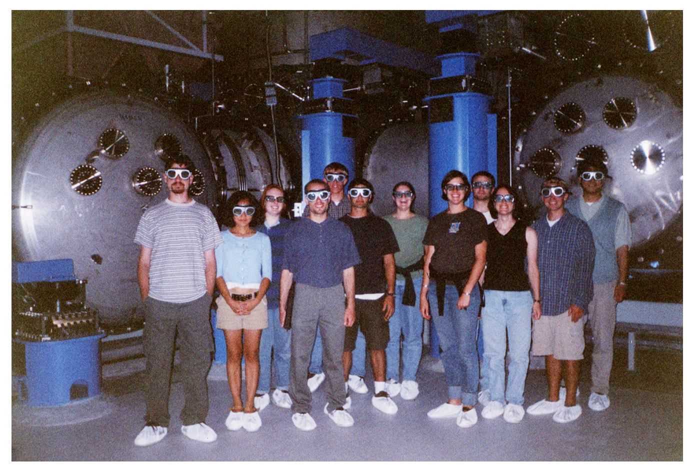


To study empty space, study empty space

CERN/Fermilab: $\mathrm{TeV}^{-1} \sim 10^{-18}$ m: particle interactions

LIGO/GEO600: $\sim 10^{-18}$ m, coherent over $\sim 10^{3}$ m baseline:
Positions of massive bodies
Best way to study “empty” space(time)

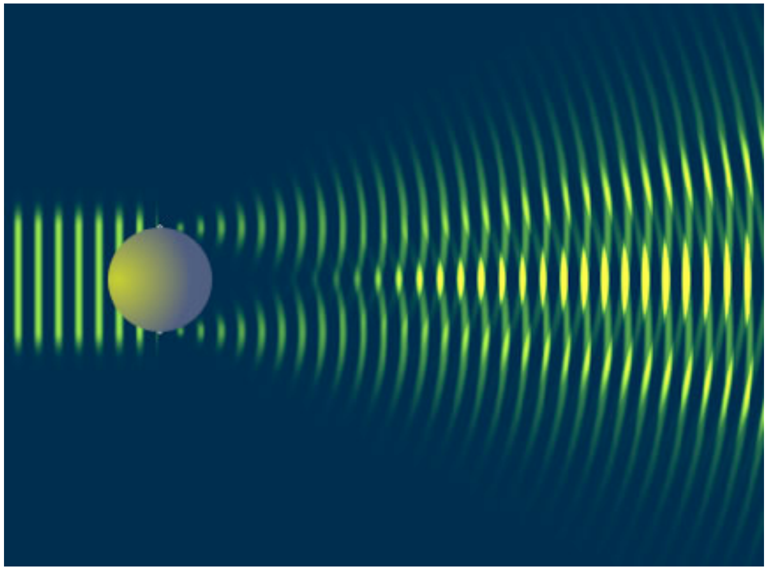
A new phenomenon?: holographic noise

- The minimum interval of time may affect interferometers
- Transverse uncertainty much larger than Planck scale in holographic theories
- precise, zero-parameter prediction of “Holographic Noise”

“Planck diffraction limit” at *L*

$$\Delta x \sim \sqrt{\lambda L}$$

is >> Planck length

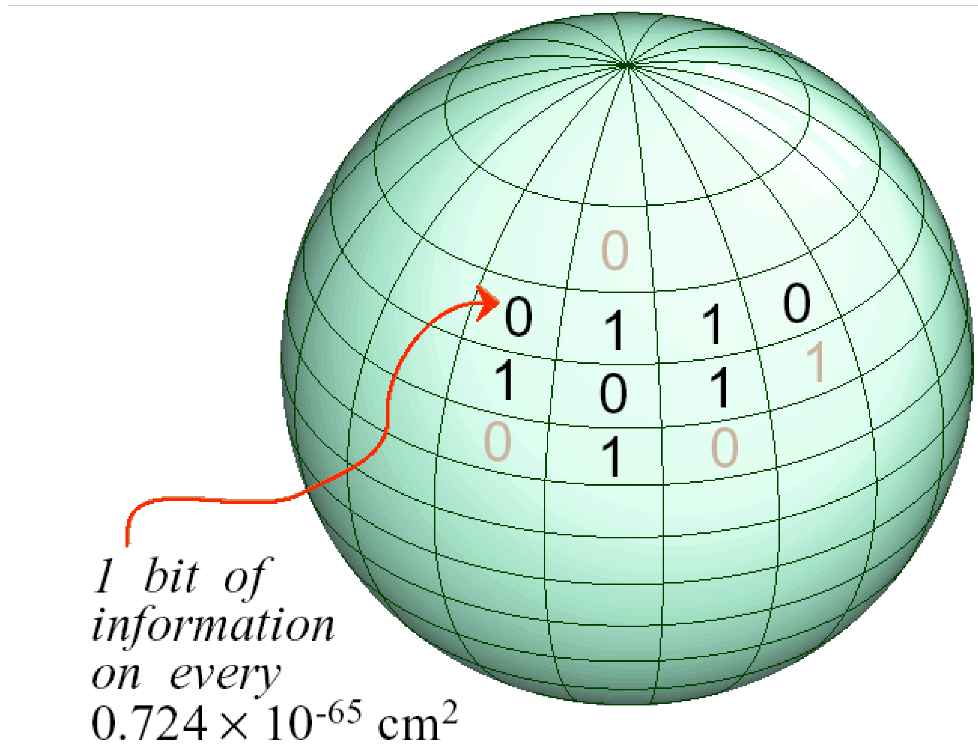


Is the world a hologram?

"This is what we found out about Nature's book keeping system: the data can be written onto a surface, and the pen with which the data are written has a finite size."

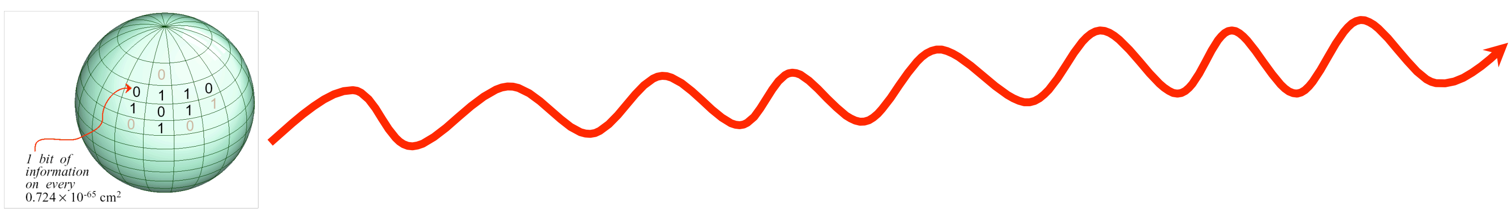
-Gerard 't Hooft

Maybe everything about the 3D world can be encoded on a 2D null surface at Planck resolution

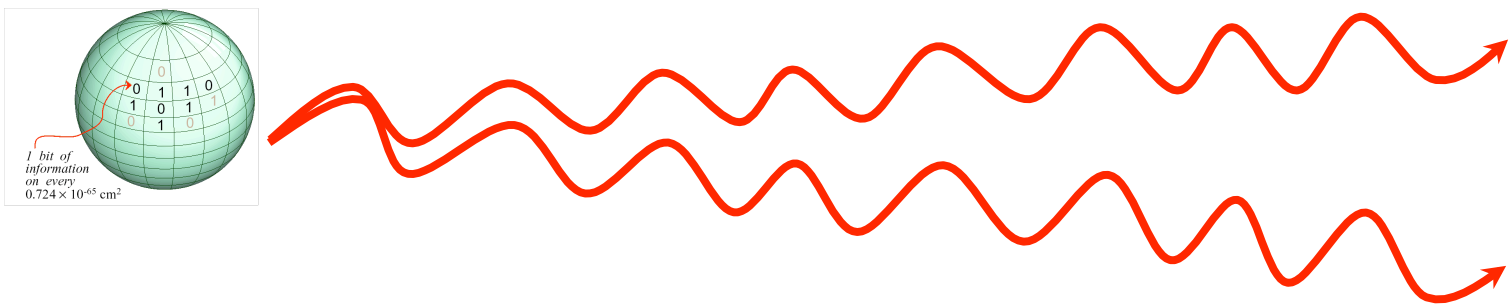


Black Hole Evaporation

- Hawking (1975): black holes radiate ~thermal radiation, lose energy and disappear
- evaporated quanta carry off degrees of freedom (~1 per particle) as area decreases
- States on 2D event horizon completely account for information of evaporated states, assembly histories
- Information of evaporated particles=entropy of hole= A/4

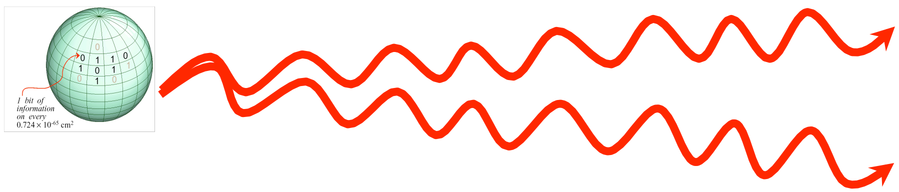


black hole evaporation can obey quantum mechanics only if distant flat space is indeterminate



If the quantum states of the evaporated particles allowed relative transverse position observables with arbitrary angular precision, at large distance they would contain more information than the hole

Holographic indeterminacy and black hole evaporation



$$(L/\Delta x)^2 < (R/\lambda)^2$$

- ~ One particle evaporated per Planck area
- position recorded on film at distance *L*
- wavelength ~ hole size *R,* standard position uncertainty

$$\Delta x > R$$

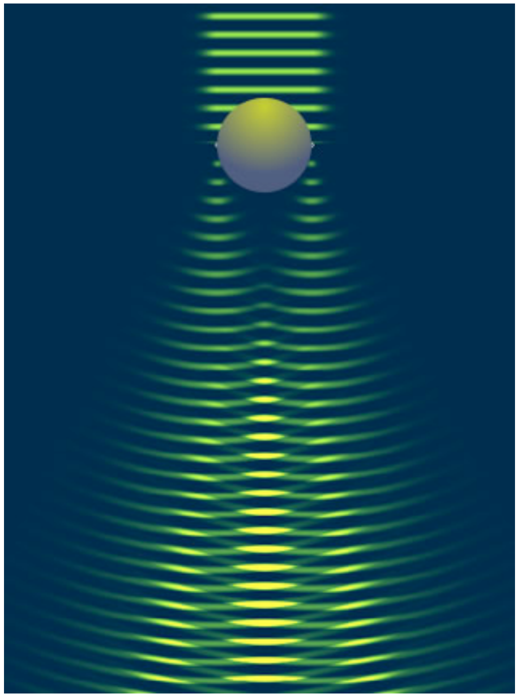
- Particle images on distant film: must have fewer “pixels” than hole
- Requires transverse uncertainty at distance *L* independent of *R*

$$\Delta x > \sqrt{\lambda L}$$

- Property of flat spacetime independent of hole
- Similarly for number of position states of an interferometer

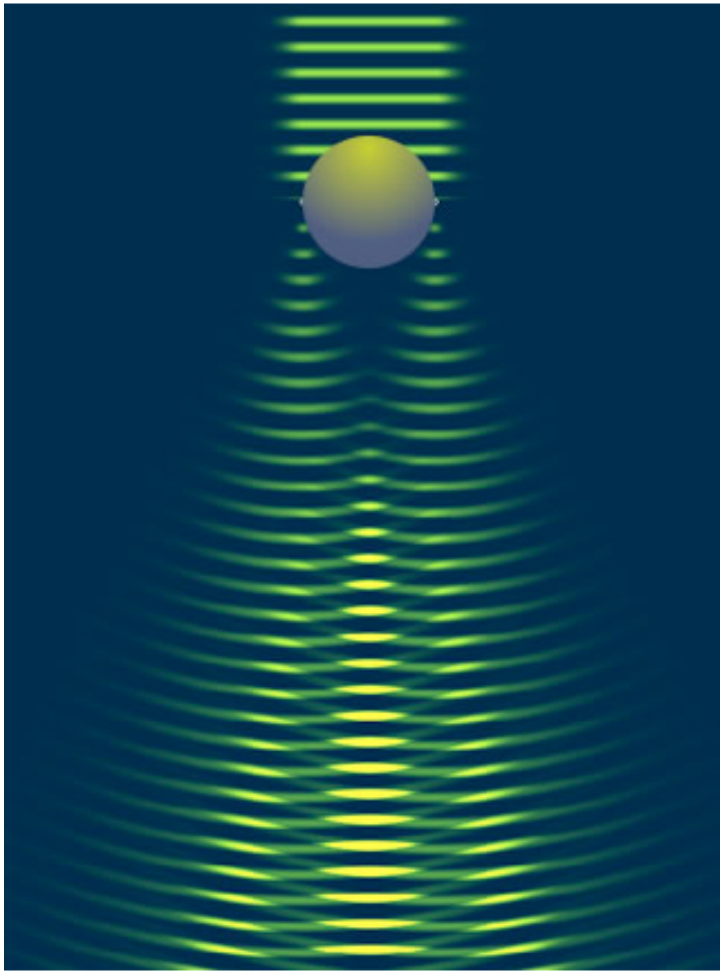
Holographic Geometry

- Spacetime is a quantum system, not a continuous classical manifold
- theory built on light sheets
- "Planck photon's view" of the world
- Planck maximum frequency
- Transverse wavefunction spreads over macroscopic distances
- transverse uncertainty in geometry much larger than Planck length

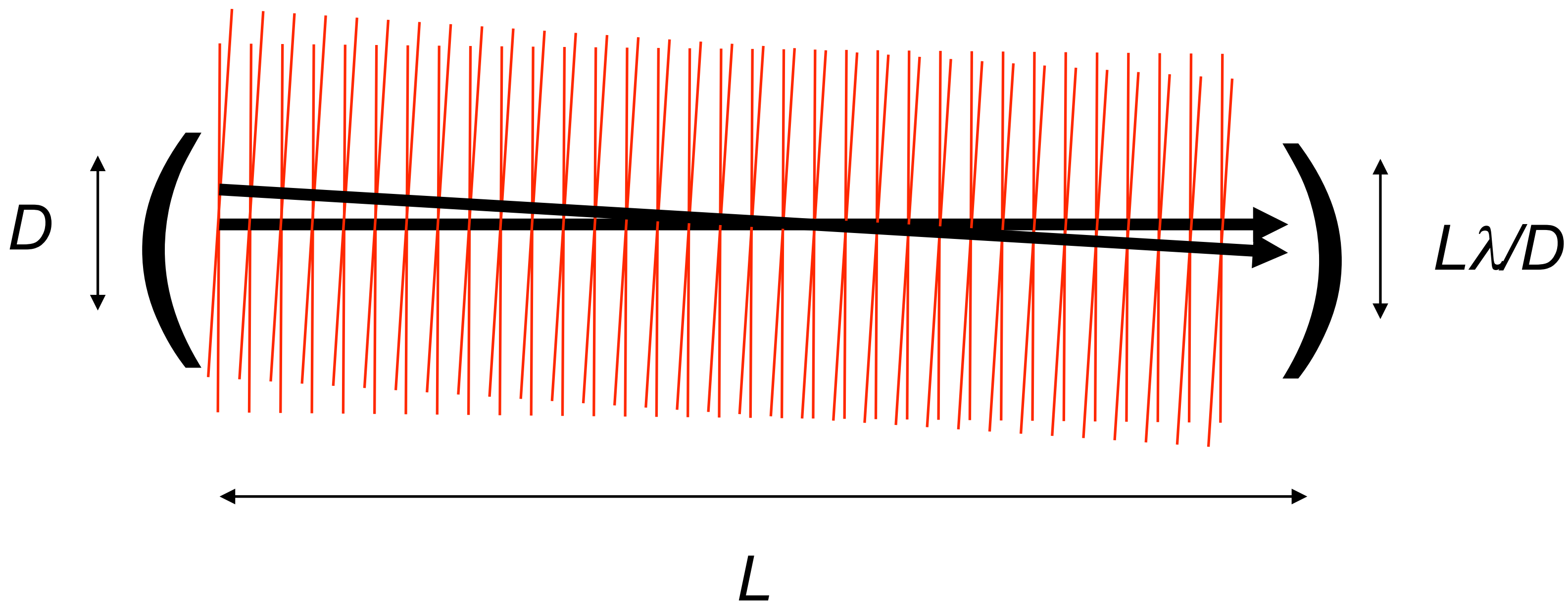


Wave Theory of Spacetime Indeterminacy

- Adapt wave optics to theory of "spacetime wavefunctions"
- transverse indeterminacy from diffraction of Planck waves
- Allows calculation of holographic noise with no parameters



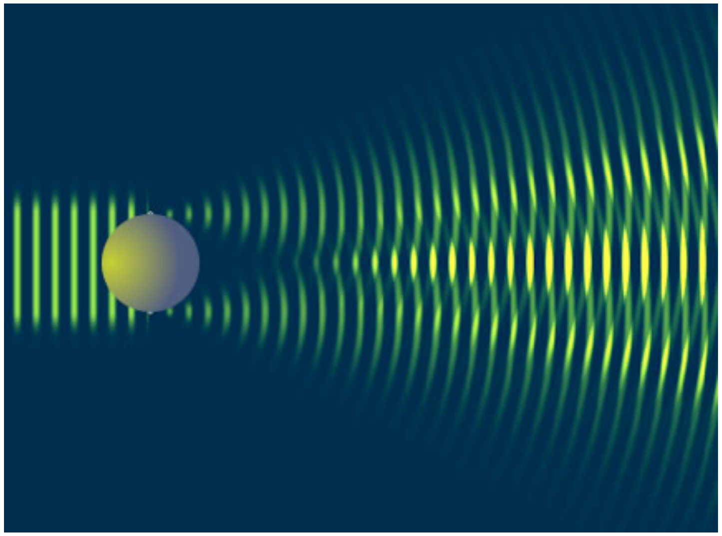
Waves and rays: Rayleigh range and transverse uncertainty

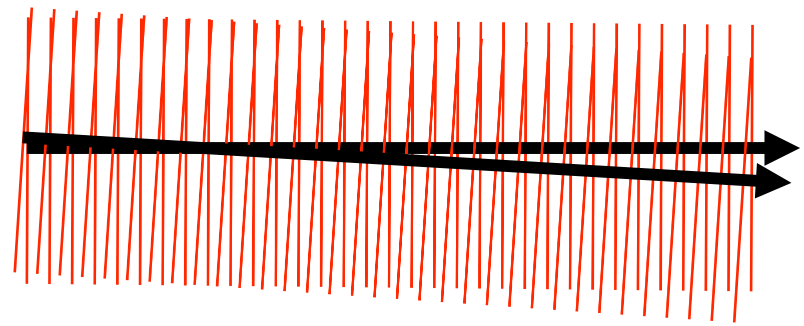


- Aperture *D*, wavelength λ *:* angular resolution λ/D
- Size of diffraction spot at distance *L: L*λ/D
- path is determined imprecisely by waves
- Minimum uncertainty at given *L* when aperture size = spot size, or

$$D = \sqrt{\lambda L}$$

Indeterminacy of a Planckian path





- Classical spacetime manifold defined by paths and events
- Path is like ray approximation of wave physics
- Indeterminacy of geometry from band-limited waves

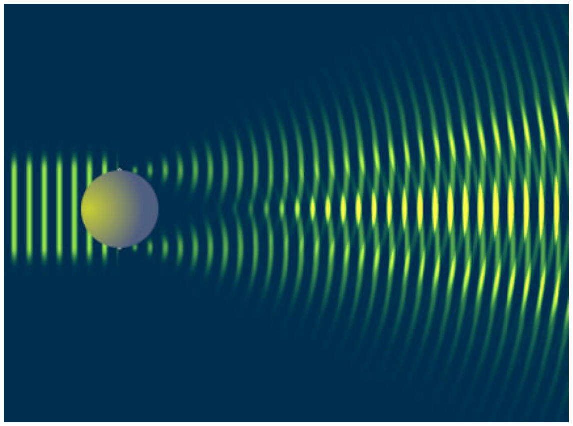
holographic approach to the classical limit

- Angles are indeterminate at the Planck scale, and become better defined at larger separations:

$$\Delta\theta(L) = (l_P/L)^{1/2}$$

- But uncertainty in relative transverse position **increases** at larger separations:

$$\Delta x_\perp^2 > l_P L$$



- Not the classical limit of field theory
- Indeterminacy and nonlocality persist to macroscopic scales

A holographic world is blurry

limited information content

What does it look like "from inside"?
("Flatland" realized with waves)

The case of a real hologram

- For optical light and a distance of about a meter,

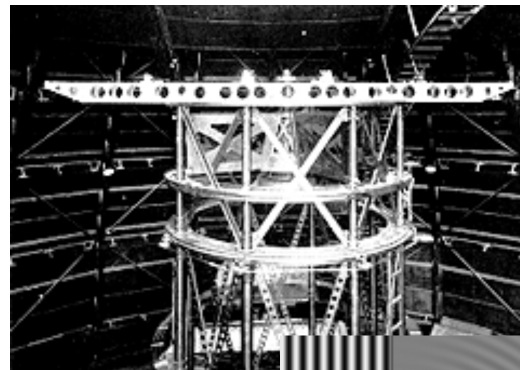
$$D = \sqrt{\lambda L}$$

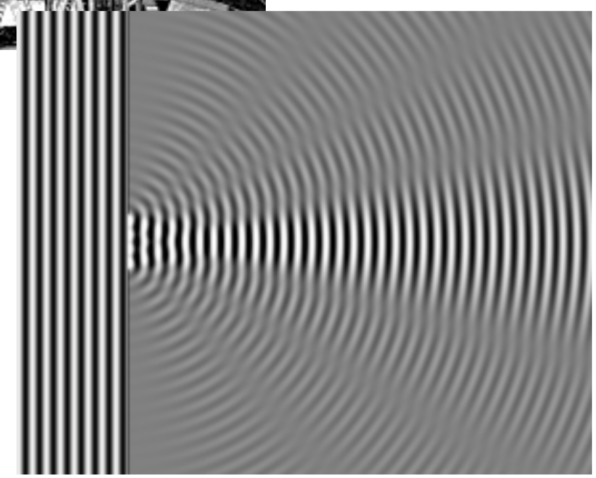
  is about a millimeter

- Larger aperture gives sharper image but then photon paths and arrival positions cannot be measured so well

- If you "lived inside" a hologram, you could tell by measuring the blurring/indeterminacy

Familiar examples from the world of optics





- Hanbury Brown-Twiss interferometry: correlation of intensity from distant star in widely separated apertures

- Michelson stellar interferometer: fringes from star

- Diffraction in the lab: shadow of plane wave cast by edge or aperture

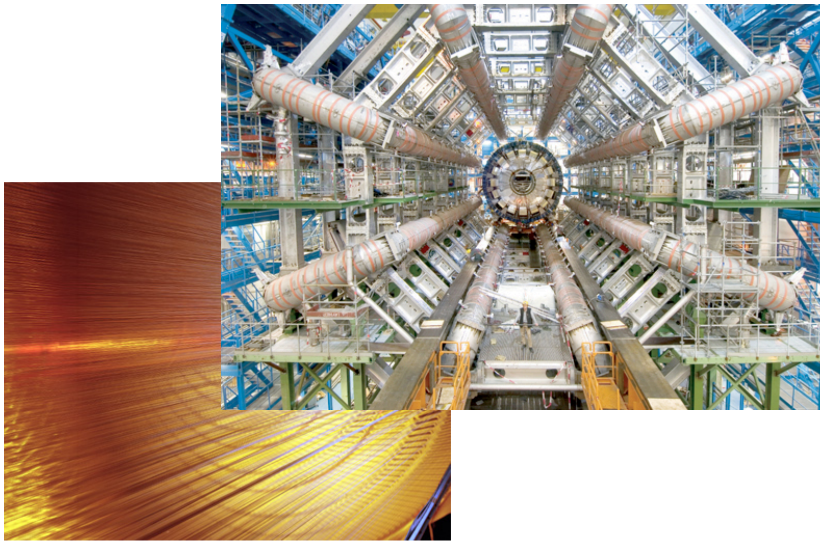
All display similar optical examples of wave phenomena much larger than the waves

Holographic Noise in Interferometers

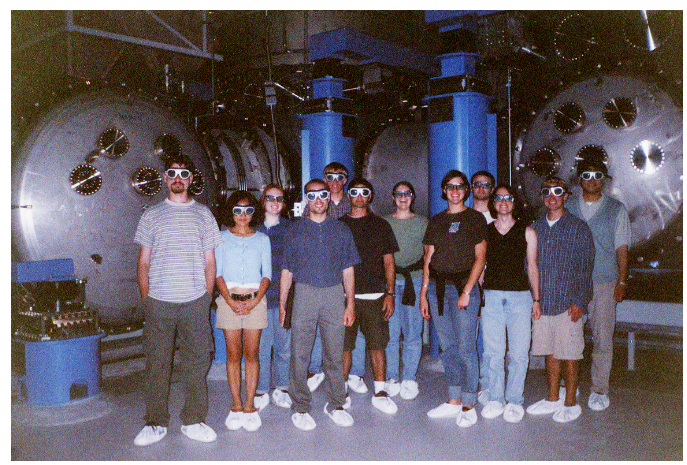
- Nonlocality: relative positions at km scale
- Fractional precision < 10^{-21}, > "halfway to Planck"
- Transverse position measured in Michelson layout
- Heavy proof masses, small Heisenberg uncertainty (SQL): positions measure spacetime wavefunction
- holographic noise appears in signal

Measurement of quantum geometry requires
coherent position measurement over macroscopic distance

CERN/FNAL: $\mathrm{TeV}^{-1} \sim 10^{-18}$ m



LIGO/GEO: $\sim 10^{-18}$ m
over $\sim 10^{3}$ m baseline



Power Spectral Density of Shear Noise

Uncertainty in angle ~ dimensionless shear

$$\Delta\theta(L) = (l_P/L)^{1/2}$$

At f=c/2L, shear fluctuations with power spectral density

$$h_H^2 \simeq L\Delta\theta^2 \approx t_P$$

h_H^2 =mean square perturbation per frequency interval

(no parameters, Planck length is the only scale)

Universal Holographic Noise

*flat power spectral density of **shear** perturbations:*

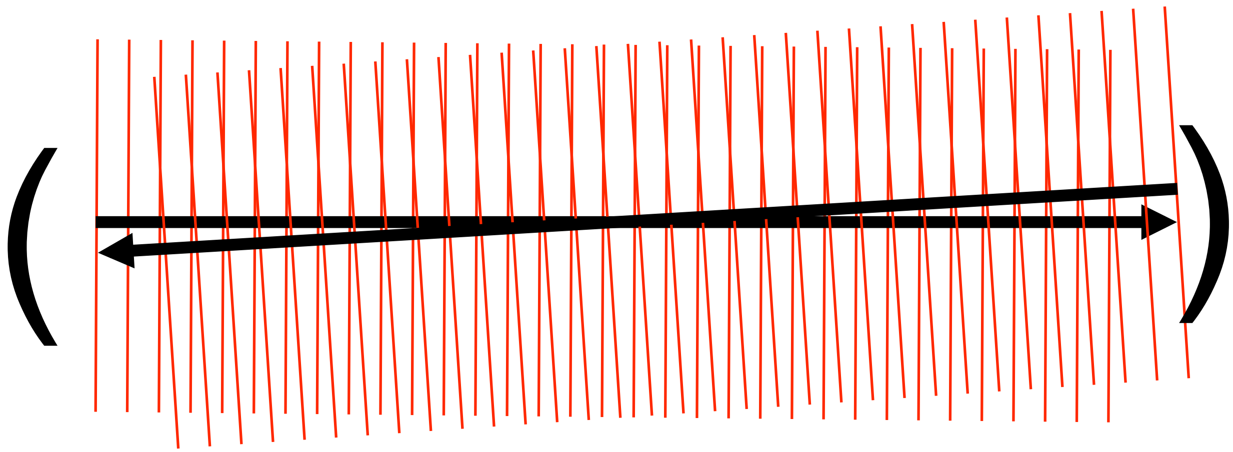
$$h \approx \sqrt{t_P} = 2.3 \times 10^{-22}\mathrm{Hz}^{-1/2}$$

- general property of holographic quantum geometry
- Prediction of spectrum with no parameters
- Prediction of spatial shear character: only detectable in transverse position observables
- Definitively falsifiable

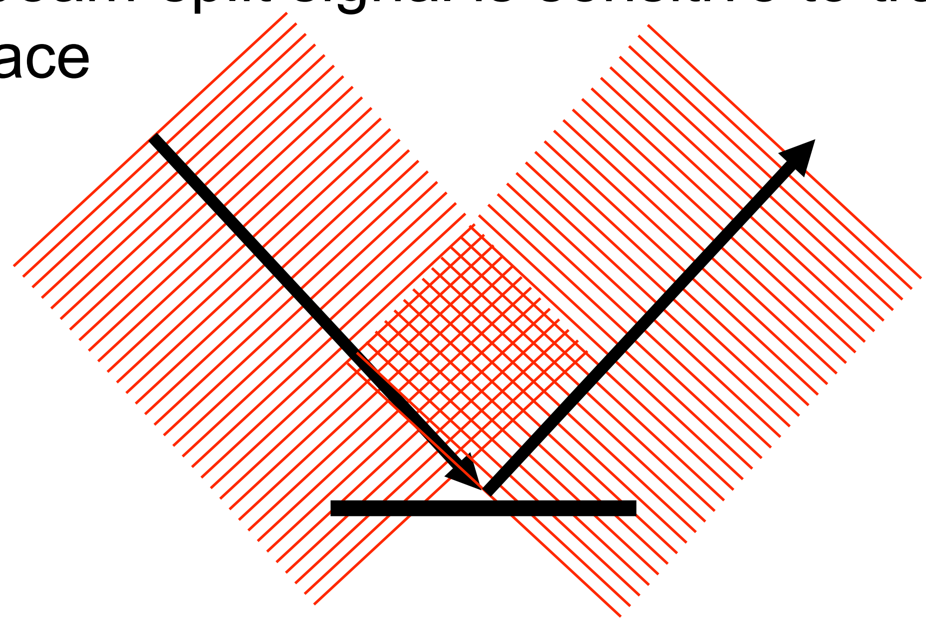
Holographic noise does not carry energy or information

- ~ classical gauge mode (flat space, no classical spacetime degrees of freedom excited)
- ~sampling or pixelation noise, not thermal noise
- Bandwidth limit of reality
- no strain, just shear
- no detectable effect in a purely radial measurement

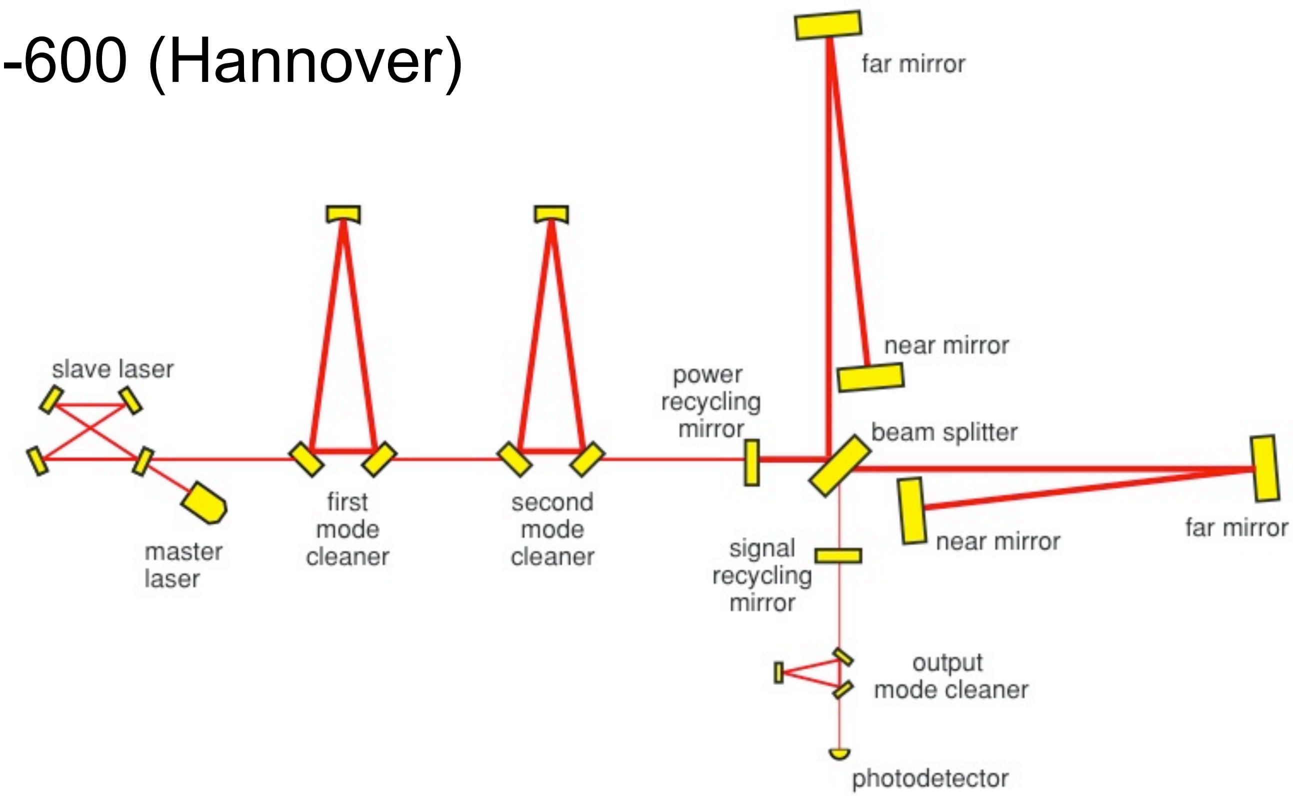
Normal incidence optics: phase signal does not record the transverse position of a surface



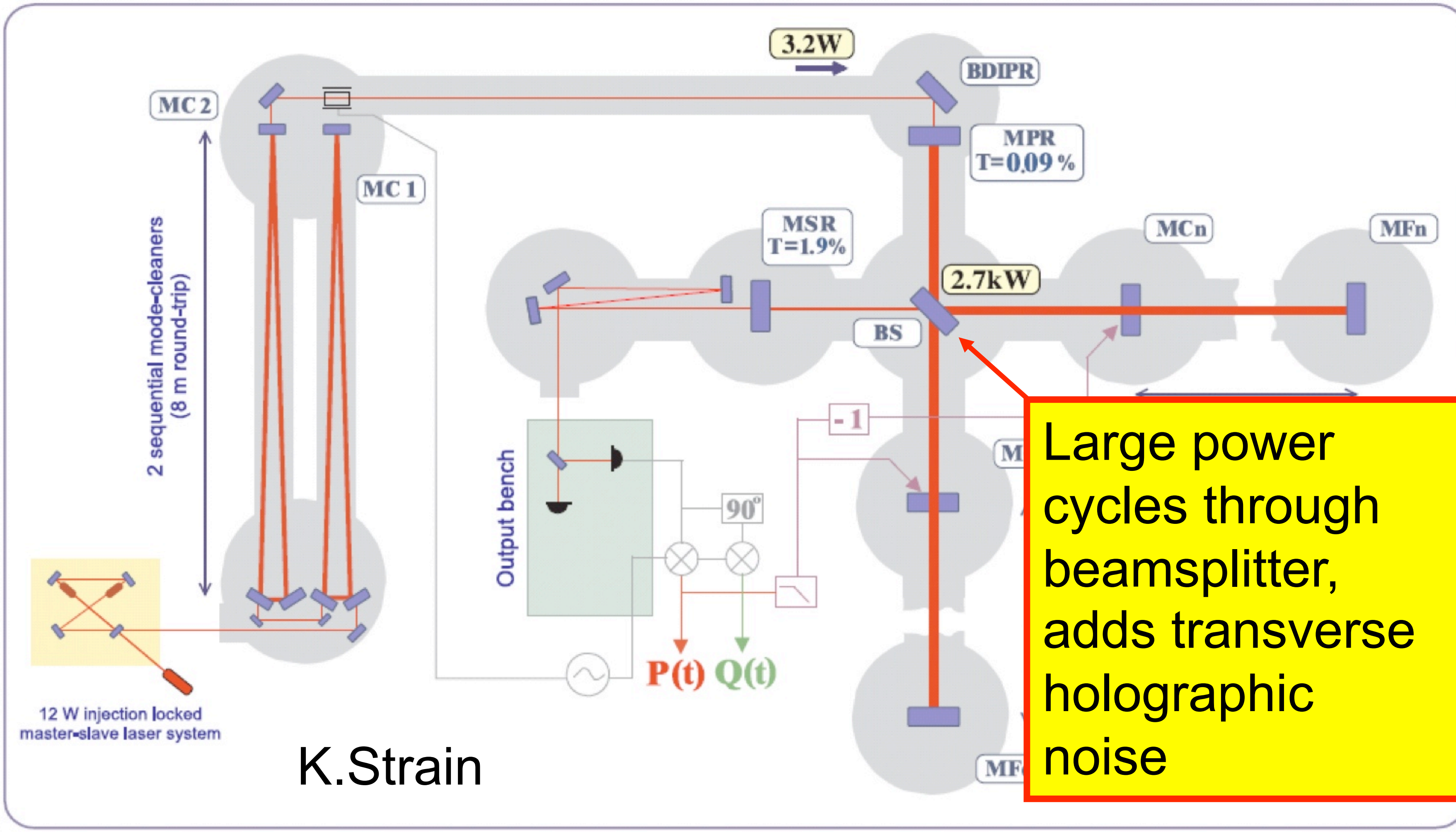
- But phase of beam-split signal is sensitive to transverse position of surface



GEO-600 (Hannover)



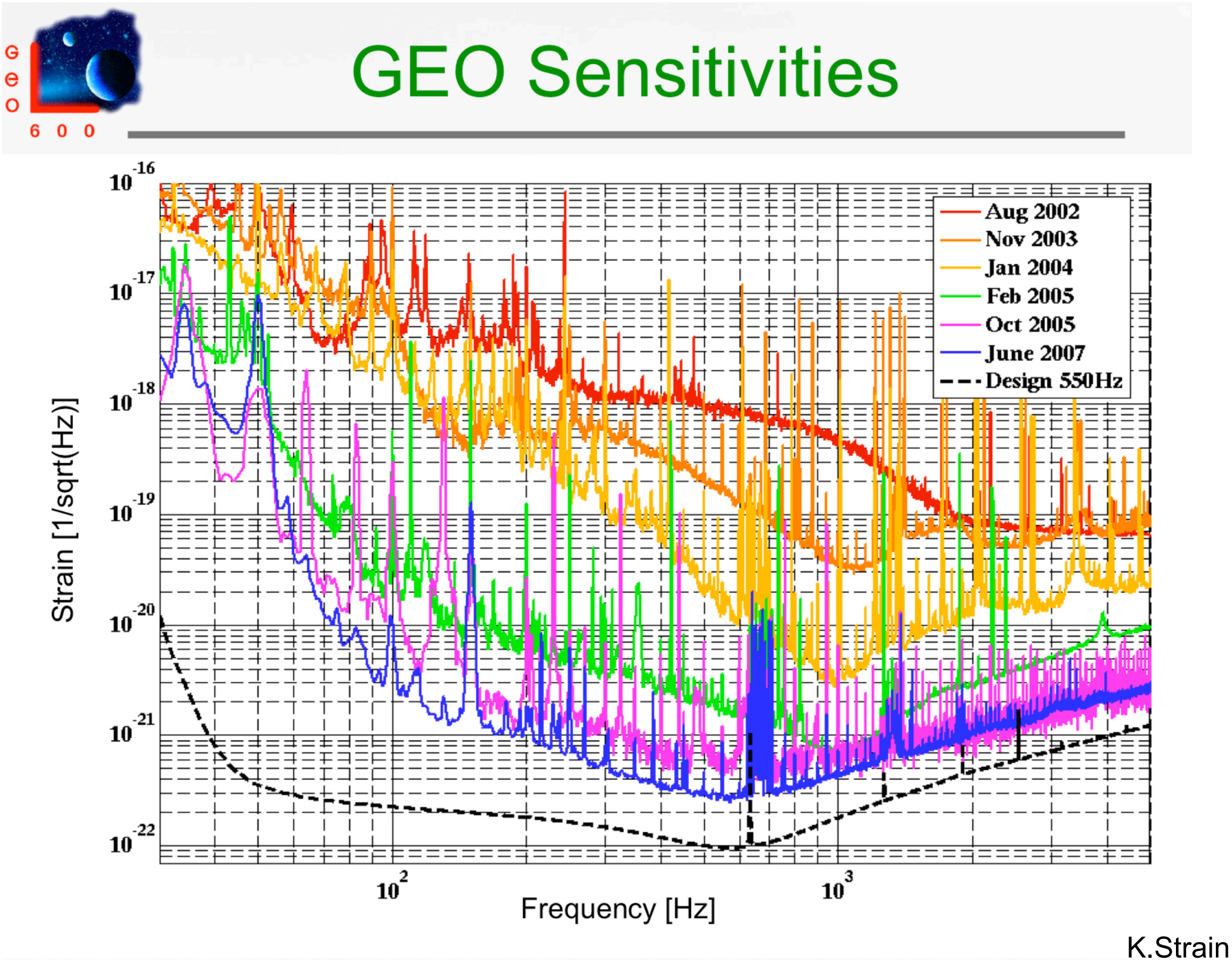
The GEO600 Interferometer



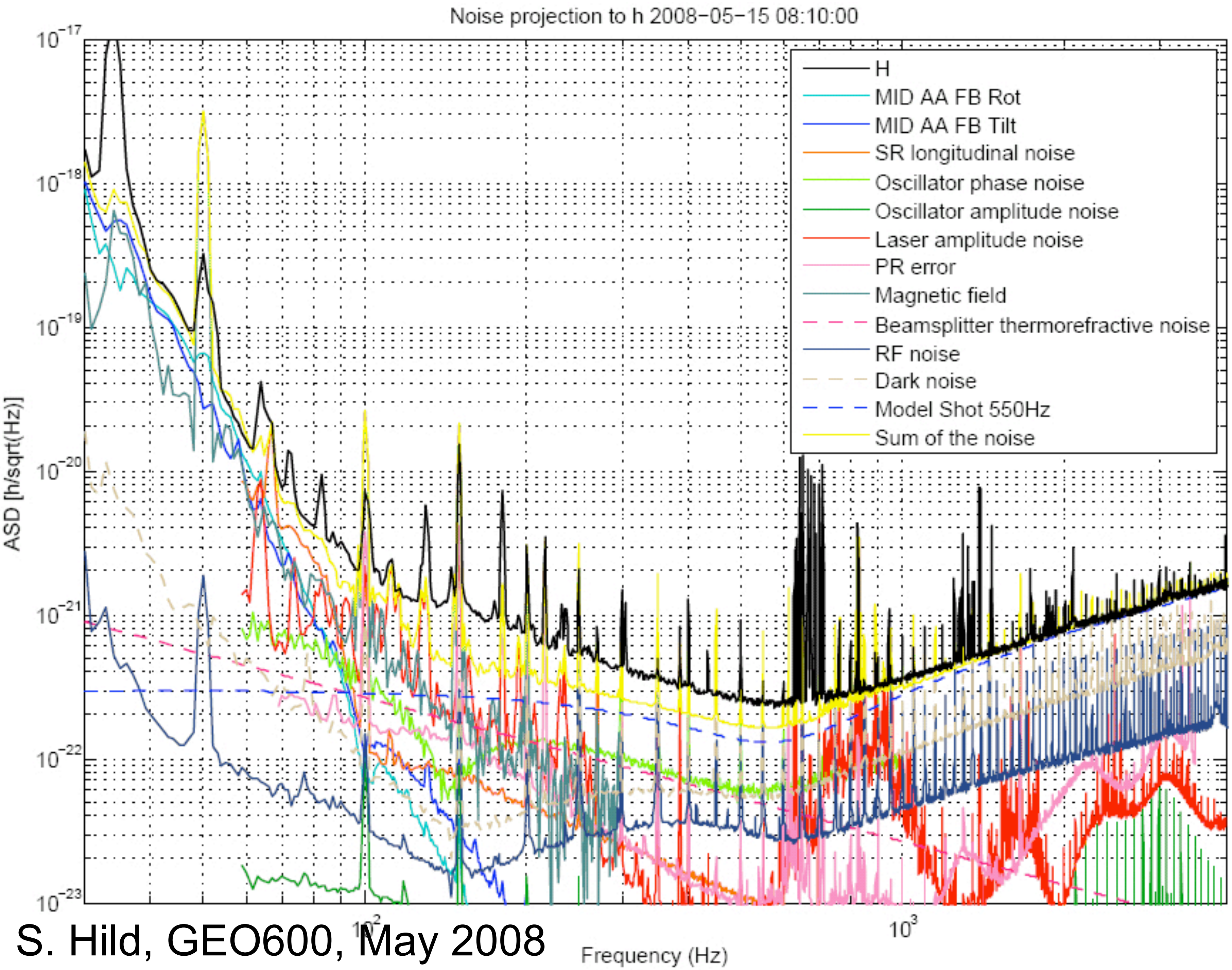
K.Strain

Large power cycles through beamsplitter, adds transverse holographic noise

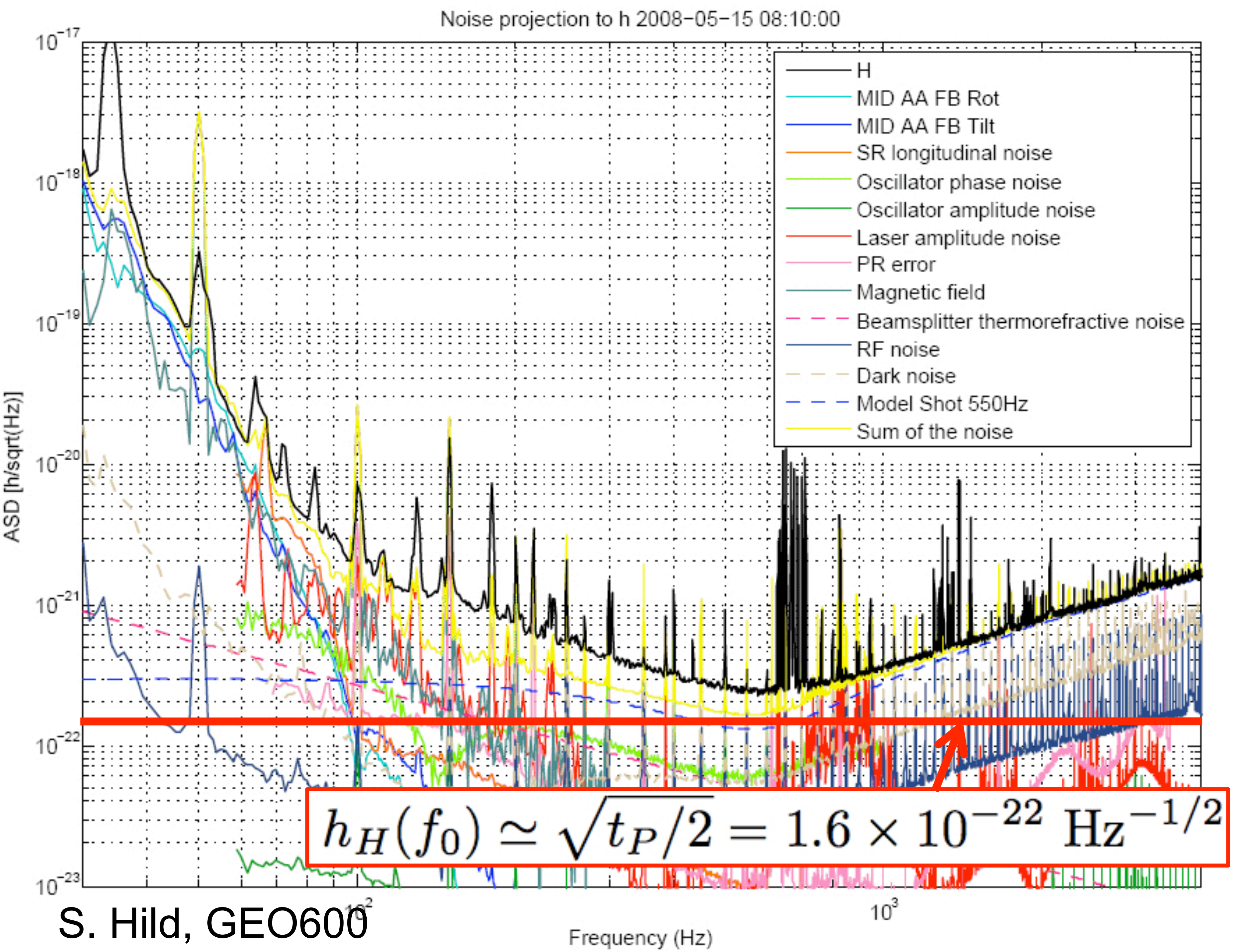
Noise in GEO600 over time



H. Lück, S. Hild, K. Danzmann, K. Strain



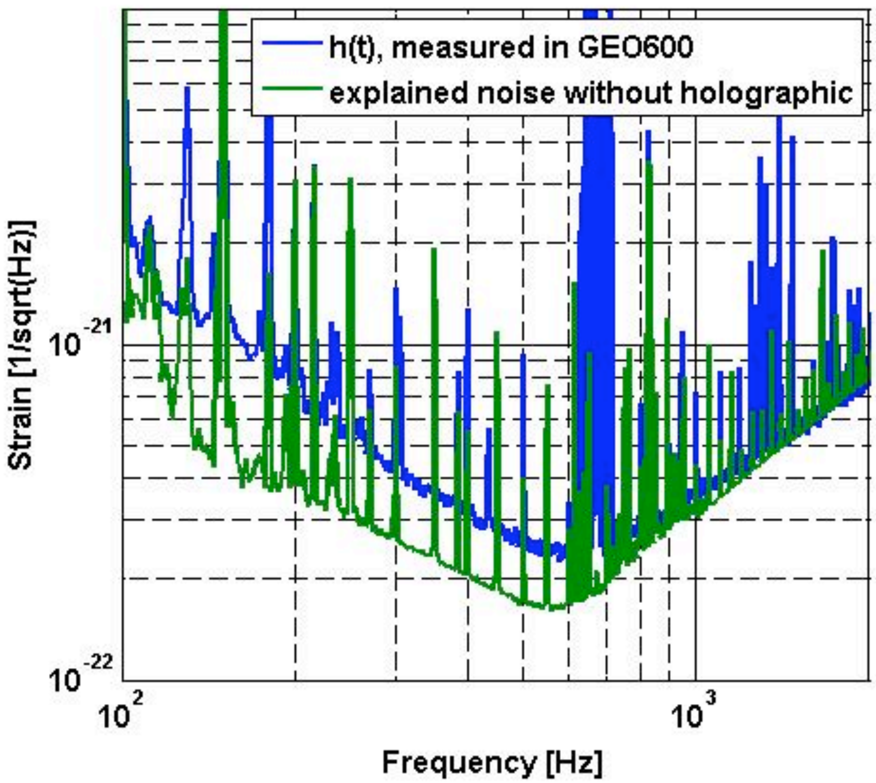
S. Hild, GEO600, May 2008

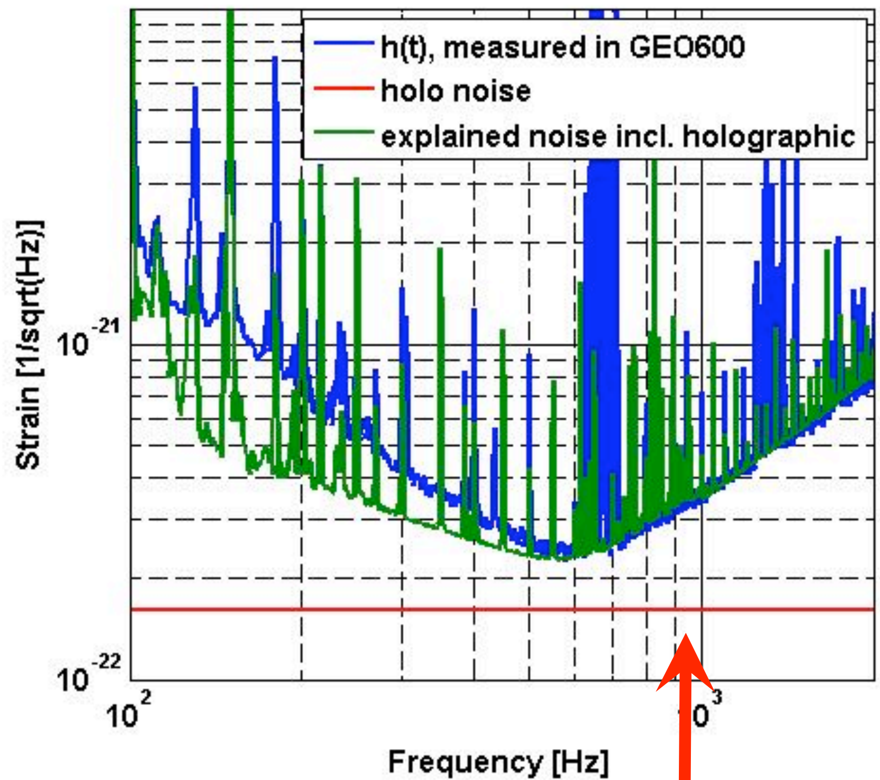


$$h_H(f_0) \simeq \sqrt{t_P/2} = 1.6 \times 10^{-22}\ \mathrm{Hz}^{-1/2}$$

S. Hild, GEO600

“Mystery Noise” in GEO600





$$\sqrt{t_{Planck}/2}$$

zero-parameter prediction for holographic noise in GEO600 (equivalent GW strain)

Data: S. Hild (GEO600)

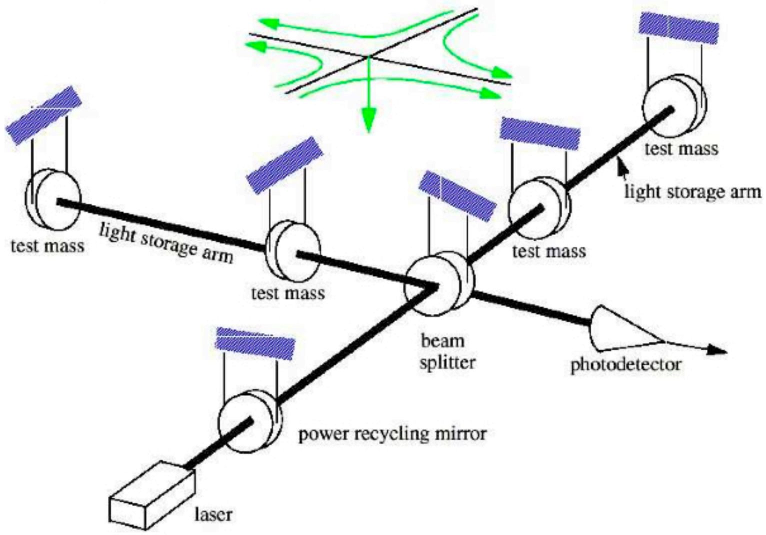
Prediction: CJH, arXiv:0806.0665
(Phys Rev D.78.087501)

Total noise: not fitted

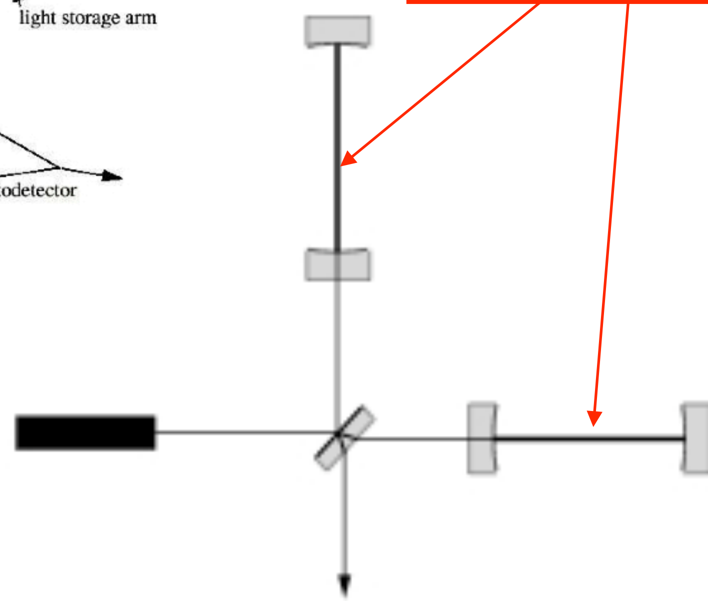
Why doesn't LIGO detect holographic noise?

- LIGO design is not as sensitive to transverse displacement noise as GEO600
- relationship of holographic to gravitational wave depends on details of the system layout

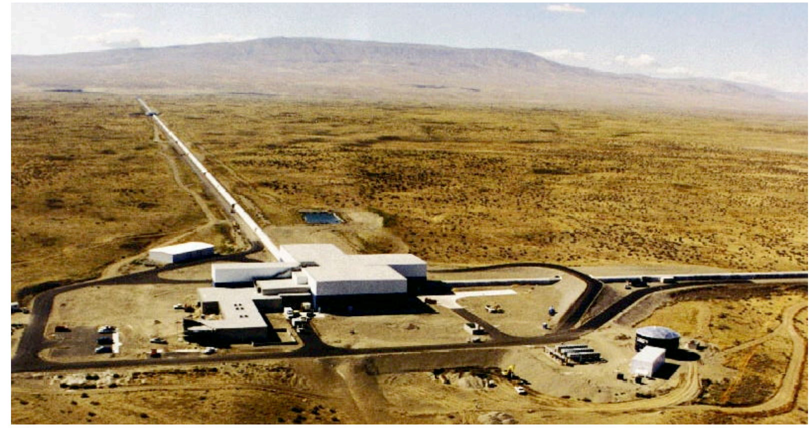
Fig. 1. Schematic layout of a LIGO interferometer.

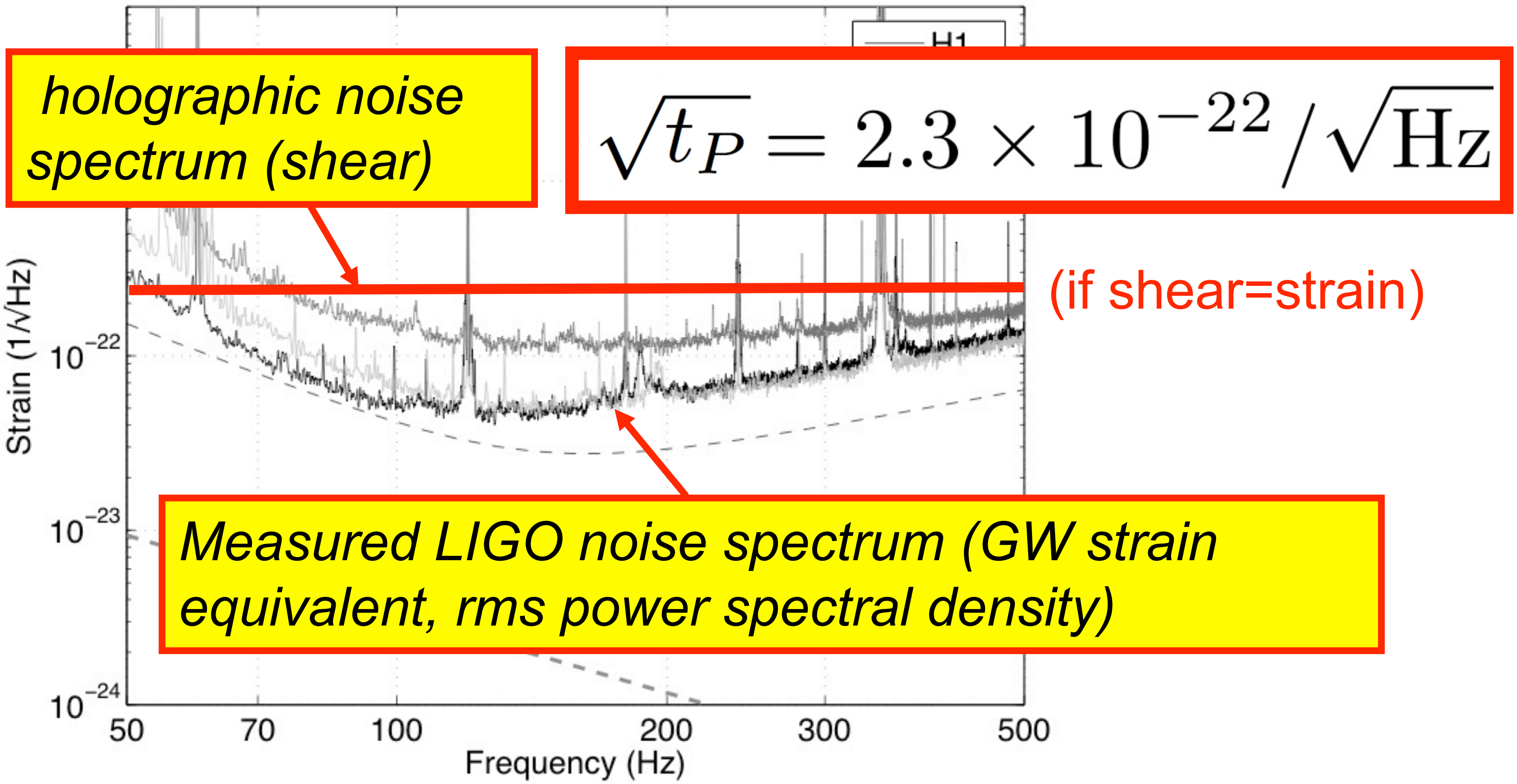


Transverse position measurement is not made in FP cavities

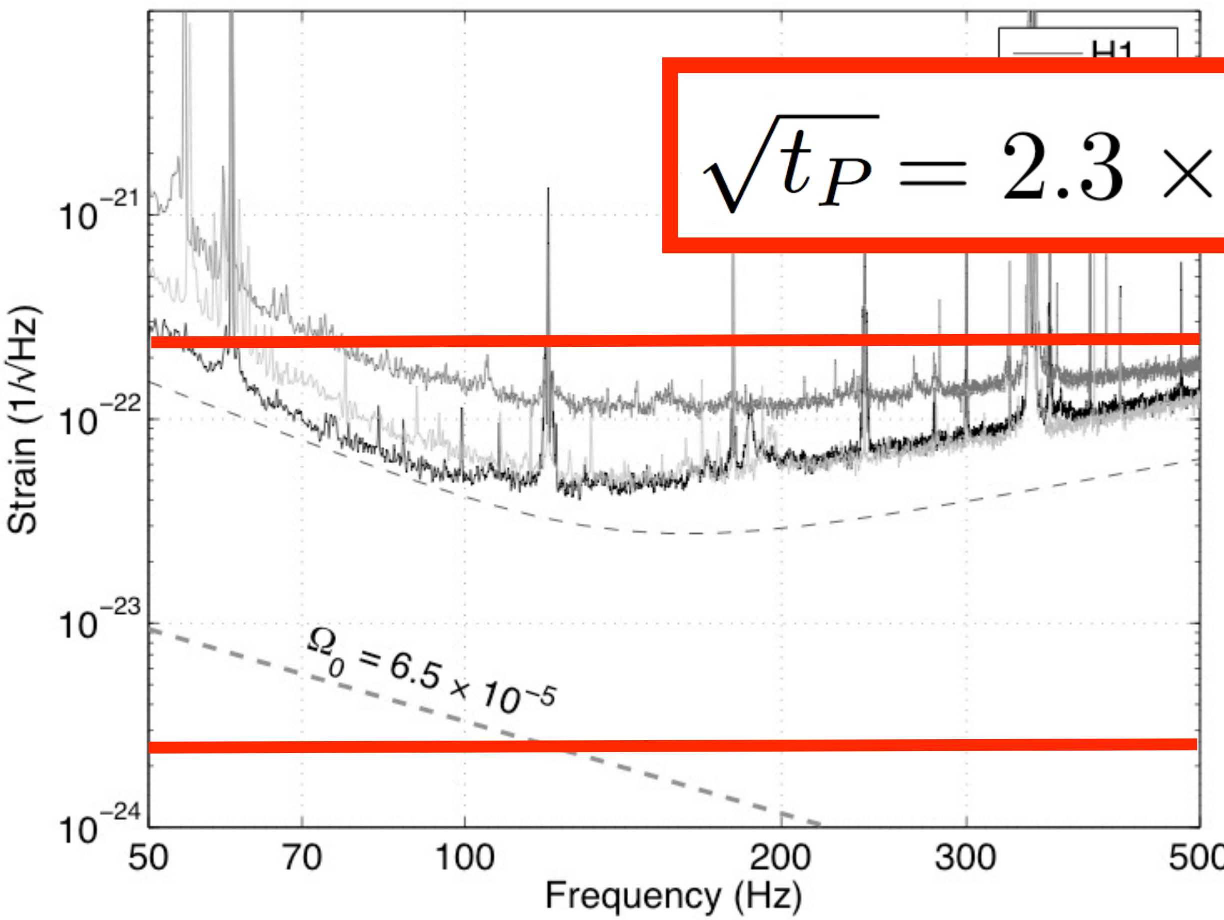


LIGO noise (astro-ph/0608606)





LIGO noise, and holographic noise prediction based on arm cavity finesse



$$\sqrt{t_P} = 2.3 \times 10^{-22} / \sqrt{\mathrm{Hz}}$$

about 100 times less

Interferometers can detect quantum indeterminacy of holographic geometry

- Beamsplitter position indeterminacy inserts holographic noise into signal
- **system with GEO600 technology can detect holographic noise if it exists**
- Signatures: spectrum, spatial shear

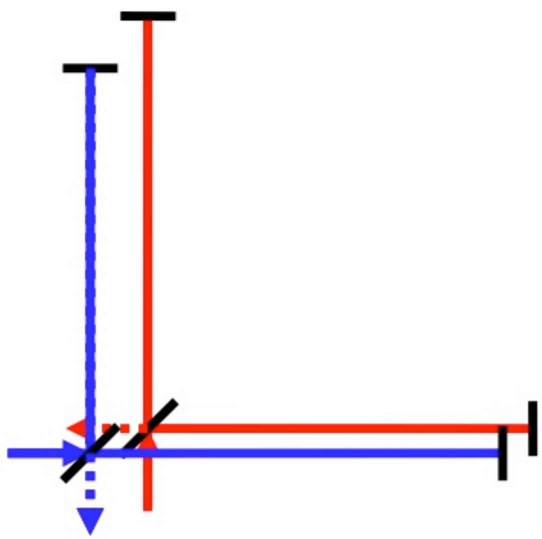
CJH: Phys. Rev. D 77, 104031 (2008); **arXiv:0806.0665**

Current experiments: summary

- Most sensitive device, GEO600, sees noise compatible with holographic spacetime indeterminacy
- requires testing and confirmation!
- H. Lück: "...it is way too early to claim we might have seen something.”
- But GEO600 is operating at holographic noise limit
- LIGO: current system not sensitive enough, awaits upgrade

Dedicated holographic noise experiments: beyond GW detectors

- f ~100 to 1000 Hz with GW machines
- f ~ MHz possible with new apparatus on ~40m scale
- Easier suspension, isolation, optics, vacuum, smaller scale
- Correlated holographic noise in adjacent paths: signature of holographic effect

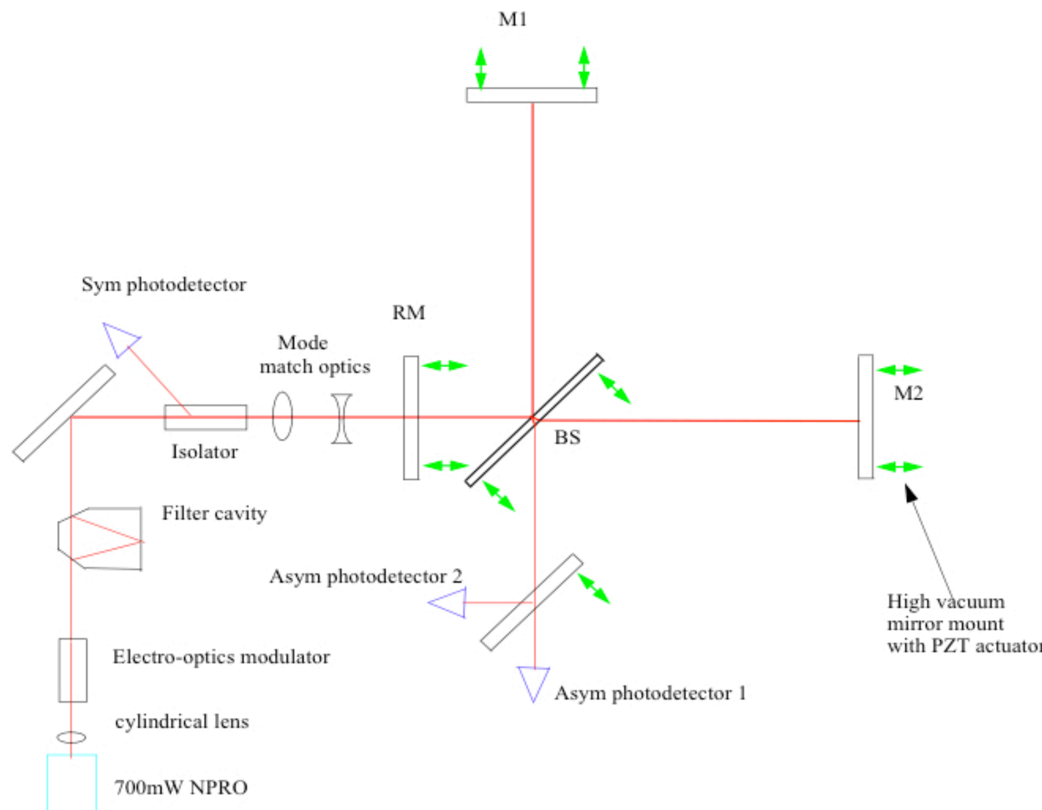


Conceptual Design from Rai Weiss

Two ~40m Michelson interferometers in coincidence

~1000 W cavity

holographic noise= laser photon shot noise in ~5 minutes (1 sigma)



Currently discussing: Fermilab (CJH, Chou, Wester, Steffen, Ramberg, Gustafson, Tomlin), MIT (Weiss, Waldman), Caltech (Whitcomb, Ballmer), AEI (Danzmann, Lück, Hild, Grote), UC (Meyer)

Next Steps

- GEO600 upgrades/retuning/ sample at free spectral range (125 kHz)
- New experiment at MHz frequencies for a convincing test
- Future: other technologies for measuring high precision, low noise, nonlocal relative transverse positions (e.g., atom interferometers)

Experimental science of holographic noise

- Measure fundamental interval of time
- Measure all physical degrees of freedom: explore physics "from above"
- Compare with Planck time derived from Newton's *G:* test fundamental theory
- Test predictions for spectrum and spatial correlations: properties of holographic geometry
- Connect with quantum physics of Dark Energy, inflationary fluctuations